TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

LASSE KAUTTO

PERFORMANCE REQUIREMENTS SPECIFIC FOR NUCLEAR EMERGENCY DIESEL GENERATING (EDG) SYSTEM

Master of Science Thesis

Examiner: Professor Risto Raiko

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ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
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Nuclear power plants (NPPs) are equipped with several independent safety systems, which purpose is to prevent possible failure situations and accidents that may disturb normal operation of the NPP and cause damage to a reactor. One important NPP safety system application is an emergency diesel generating (EDG) system that operates as an on-site emergency power supply system for the NPP. Its main purpose is to generate and supply electricity to NPP's necessary safety and control systems (safety auxiliaries) in case of regular power supply from an off-site electricity grid fails (loss-of-offsite power, LOOP) and during other critical emergency events. The EDG system consists of a large diesel engine, a generator, a common base frame, auxiliary systems, and control and instrumentation equipment that all ensure proper function of the entire system.

The main goal of this study is to examine and discover what are the most important performance requirements specific for the nuclear EDG system. In order to achieve this aim, this thesis carries out a comprehensive review of the EDG system's components and their functions based on Wärtsilä's technology. In addition, it investigates topics such as the role of the EDG system operating with the NPP, applicable nuclear regulations, standards and frameworks, applicable qualification procedures and possible factors influencing the EDG system's performance. Instead of numerical and calculation based approach, the performance of the EDG system is studied mainly from functional side.

This study indicates that the necessary safety functions of the EDG system form a foundation for the most important performance requirements such as fast start-up in response to emergency demand, accepting and accelerating heavy motor loads in rapid succession to constant rotational speed, maintain load within acceptable frequency and voltage limits, etc. even under abnormal operating conditions. In order to achieve demanded capability for the nuclear service, the EDG system must successfully pass rigorous qualification programs such as performance testing, analysis, and environmental qualification. From the manufacturer point of view, design, manufacturing and qualification of this particular application's equipment are challenging, and require strong know-how, constant research and development as well as keeping up to date regarding nuclear regulations and applicable standards.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Konetekniikan koulutusohjelma
KAUTTO, LASSE: Ydinvoimalaitoksen hätädieselgeneraattorijärjestelmän vaatimukset suorituskykyyn liittyen
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Ydinvoimalaitokset ovat varustettu useilla toisistaan riippumattomilla turvallisuusjärjestelmillä, joiden tarkoitus on estää mahdollisia vikatilanteita ja onnettomuuksia, jotka voivat häiritä ydinvoimalaitoksen normaalia käyttöä ja aiheuttaa vaurioita reaktorille. Eräs tärkeä ydinvoimalaitoksen turvallisuusjärjestelmiin kuuluva sovellutus on hätädieselgeneraattorijärjestelmä, joka toimii varasähkönsyöttöjärjestelmänä ydinvoimalaitoksella. Sen tärkein tarkoitus on tuottaa ja syöttää varasähköä ydinvoimalaitoksen omille turvallisuus- ja ohjausjärjestelmille, jos normaali sähkönsyöttö ulkoisesta sähköverkosta menetetään ja muiden kriittisten hätätilanteiden aikana. Hätädieselgeneraattorijärjestelmä koostuu suurikokoisesta dieselmoottorista, generaattorista, niiden yhteisestä tukialustasta, apujärjestelmistä sekä ohjaus- ja instrumentaatiolaitteista, jotka yhdessä varmistavat koko järjestelmän oikeanlaisen toiminnan.

Tämän työn päätavoitteena on tutkia ja selvittää mitkä ovat tärkeimmät ydinvoimalaitoksen hätädieselgeneraattorijärjestelmän vaatimukset suorituskykyyn liittyen. Jotta tämä tavoite saavutetaan, työ tarjoaa kattavan katsauksen hätädieselgeneraattorijärjestelmän komponentteihin ja niiden toimintoihin perustuen Wärtsilän teknologiaan. Lisäksi työssä tarkastellaan hätädieselgeneraattorijärjestelmän roolia ydinvoimalaitoksella, soveltuvia ydinvoimasäädöksiä, -standardeja ja -viitekehyksiä, soveltuvia kelpoistamismenetelmiä ja mahdollisia suorituskykyyn vaikuttavia tekijöitä. Numeerisen ja laskennallisen lähestymistavan sijaan, hätädieselgeneraattorijärjestelmän suorituskykyä tarkastellaan pääasiassa toiminnalliselta puolelta.

Työ osoittaa, että hätädieselgeneraattorijärjestelmän välttämättömät turvallisuustoiminnot muodostavat perustan tärkeimmille suorituskykyvaatimuksille kuten nopea käynnistyminen hätätilanteen vasteena, raskaiden moottorikuormien vastaanottaminen ja nopea kiihdyttäminen vakio-pyörimisnopeuteen, kuorman ylläpitäminen hyväksyttävien taajuus- ja jänniterajojen sisällä, jne. jopa epänormaalien toimintaolosuhteiden vallitessa. Kyetäkseen toimimaan ydinvoimakäytössä, hätädieselgeneraattorijärjestelmän täytyy läpäistä onnistuneesti tiukat kelpoistamisohjelmat kuten suorituskykytestauksen, analyysit, ja kelpoistuksen ympäristöolosuhteita vastaan. Laitevalmistajan kannalta kyseisen sovellutuksen laitteiston suunnittelu, valmistaminen ja kelpostaminen on haastavaa, ja edellyttää vahvaa tietotaitoa, jatkuvaa tutkimusta ja kehittämistä sekä ajan tasalla pysymistä ydinvoimasäädöksistä ja sovellettavista standardeista.

PREFACE AND ACKNOWLEDGEMENTS

This Master's thesis is written for Wärtsilä Finland Oy. The thesis project was initiated while employed by Wärtsilä in Runsor premises in Vaasa, as a trainee and member of the Nuclear Business Sales Team from May 2013 to August 2014. The majority of this thesis has been carried out during 2014 – 2016.

As a rookie in the combustion engine technology and nuclear energy field, the learning curve was rather steep. The challenges of creating this study included not only the complexity of the topic, but also the limitations in my language skills. In any case, I hope that this work clarifies this complexity and offers useful information for the experts in the field related to this study.

I would like to thank Hannu Jeronen and Juha Kerttula for instructing and guiding me during the project. I am also grateful to the professor Risto Raiko for examining this thesis and giving feedback. In addition, I want to express my thanks to entire Nuclear Sales Team and its director Bjarne Forsbacka for providing opportunity to learn this particular business area. Special thanks go also to my Wärtsilä colleagues, especially to Janne Heikka, Sari Vehkanen and Teemu Sipilä for continuous support, inspiring conversations and creating such a joyful working atmosphere in the office and also outside of it. Also other Wärtsilä staff assisting my research work deserves acknowledgements. Last but not least, I would like to thank my family and especially my sister Niina, for advising, constant encouragement, understanding and care.

Jyväskylä, August 24th of 2016

Lasse Kautto

CONTENTS

TERMS AND ABBREVIATIONS

1-C	One-Circuit
2-C	Two-Circuit
AC	Alternating Current
AVR	Automatic Voltage Regulator
AWG	Air Waste Gate
BDC	Bottom Dead Center
BFL	Biofuel
BWR	Boiling Water Reactor
CAC	Charge Air Cooler
CB	Circuit Breaker
CCF	Common Cause Failure
CANDU	Canada Deuterium-Uranium reactor
DBE	Design Basis Event
DC	Direct Current
DG	Diesel Generator
E&A	Electrical and Automation
EDG	Emergency Diesel Generator/Generating System
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPC	Engineering, Procurement and Construction
EPR	European Pressurized Reactor
ESD	Electrostatic Discharge
ESF	Engineered Safety Features
EWG	Exhaust Waste Gate
EYT	Ei Ydinteknisesti Turvallisuusluokiteltu
FAT	Factory Acceptance Testing
FMEA	Failure Mode Effect Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
HEMP	High-Power Electromagnetic Pulse
HFO	Heavy Fuel Oil
HMI	Human Machine Interface
HT	High Temperature
I&C	Instrumentation and Control
LCP	Local Control Panel
LFO	Light Fuel Oil
LO	Lubricating Oil
LOC	Lubricating Oil Cooler
LOCA	Loss of Coolant Accident
LOOP	Loss of Off-site Power
LT	Low Temperature
LV	Low Voltage
LWR	Light Water Reactor
MCB	Miniature Circuit Breaker
MCR	Main Control Room
MV	Medium Voltage
NC	Normal Closed
NO	Normal Open
NPP	Nuclear Power Plant

NSR	Non-Safety Related
OBE	Operating Basis Earthquake
PF	Power Factor
PMG	Permanent Magnet Generator
PWR	Pressurized Water Reactor
RTD	Resistance Temperature Detector
SAT	Site Acceptance Testing
SBO	Station Blackout
SC	Safety Class
SIAS	Safety Injection Actuation Signal
SLB	Steam Line Break
SPEX	Single Pipe Exhaust
SR	Safety Related
SSE	Safe Shutdown Earthquake
TC	Turbocharger
WCC	Wärtsilä Component Category

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
EN	European Standard
EPRI	Electric Power Research Institute
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRS	IAEA's incident reporting system
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
ISO	International Organization for Standardization
KTA	Kerntechnischer Ausschuss
LER	Licensee Event Reports
NEMA	National Electrical Manufacturers Association
NRC	Nuclear Regulatory Commission
RG	Regulatory Guide
SAPIDE	IRSN's incident reporting system
STUK	Säteilyturvakeskus
VERA	GRS's incident reporting system
YVL	Ydinvoimalaitosohjeet

SYMBOLS

$f_{d,max}$	Transient frequency increase, maximum, dynamic speed deviation, [%]
$f_{d,min}$	Transient frequency decrease, maximum, dynamic speed deviation, [%]
$f_{dec,max}$	Frequency decrease of nominal, maximum [%]
f_{rd}	Frequency restoration of nominal, step load decrease, [%]
f_{ri}	Frequency restoration of nominal, step load increase, [%]
h	Altitude above sea level, [m]
$n_{d,0}$	Triggering speed of the overspeed protection equipment, [min^{-1}, %]
n_{max}	Speed increase, maximum, [min^{-1}]
n_N	Nominal speed, [min^{-1}]
p	Atmospheric pressure, [Pa, bar, mm Hg]
P_{ol}	Overload power capacity limit, [%]
p_r	Total barometric pressure, reference value, [kPa]
Δp_r	Sum of exhaust gas back pressure and intake air pressure drop, reference value, [kPa]
Rh	Relative air humidity, [%]
Rh_{in}	Relative air humidity indoors, [%]
$T_{cac,r}$	Charge air coolant temperature, reference value, [K]
t_{frd}	Load sequence interval, step load decrease, frequency restoration of nominal, [%]
t_{fri}	Load sequence interval, step load increase, frequency restoration of nominal, [%]
T_{in}	EDG/engine room temperature, [K, °C]
$T_{in,\ control}$	Control/electrical room temperature, [K, °C]
$t_{load\ int}$	Loading time interval, [%]
t_{nB}	Application of maximum load level, frequency adjustment time, [s]
t_{nE}	Release of maximum load level, frequency adjustment time, [s]
T_{out}	Ambient air temperature outside, [K, °C]
T_r	Ambient air temperature, reference value, [K]
T_{raw}	Raw water temperature, [K, °C]
T_{sea}	Sea water temperature, [K, °C]
t_{UB}	Application of maximum load level, voltage adjustment time, [s]
t_{UE}	Release of maximum load level, voltage adjustment time, [s]
t_{Urd}	Load sequence interval, step load increase and decrease, voltage restoration of nominal, [%]
$U_{dec,max}$	Voltage decrease of nominal, maximum, [%]

U_r	Voltage restoration of nominal, step load increase and decrease, [%]
ΔU_s	Voltage control range, [%]
v_{wind}	Wind speed, [m/s]
α_n	Frequency tolerance band, frequency adjustment time, [%]
β_f	Static width of frequency variation, [%]
δ_s	Static speed adjustment (P-degree), [%]
φ_r	Relative humidity, reference value, [%]
σ_{DB}	Transient voltage deviation during power level increase, dynamic voltage variation, [%]
σ_{DE}	Transient voltage deviation during power level decrease, dynamic voltage variation, [%]
σ_G	Voltage accuracy, [%]

1 INTRODUCTION

1.1 Background

The utilization of nuclear power is currently experiencing so called transition period worldwide. Certain countries (e.g. Finland) intend to improve their nuclear power reserve in the future, whereas some countries (e.g. Germany) are strongly aiming to reduce their nuclear energy production by driving down existing nuclear power plants (NPPs) and replacing them for instance by means of renewable energy solutions. This decreasing trend is mainly a result of preventing and avoiding nuclear accidents such as the one that happened in Fukushima, Japan in 2011. Despite of uncertainties on how the energy should be produced in the future, the technology is most likely expected to be environmental friendly, carbon dioxide (CO_2) free and generated in a safe manner.

Finland is a good example of well executed nuclear safety. Four operating NPPs, two in Olkiluoto and two in Loviisa, have remained in adequate condition throughout their entire service life producing electricity safely and reliably to the consumers. The third reactor unit in Olkiluoto is under construction and a new NPP project that will be placed close to Pyhäjoki is going forward. Furthermore, the Finnish parliament voted to authorize construction of a fourth nuclear reactor in Olkiluoto. It was approved together with Pyhäjoki decision in 2010.

In Finland, the Finnish Radiation and Nuclear Safety Authority (STUK) is an independent regulatory body that supervises and regulates the use of nuclear energy. The objects of nuclear safety regulation are NPPs, nuclear materials and nuclear waste. Main tasks of STUK include formulation of detailed safety requirements concerning the use of nuclear energy and ensuring that NPPs and operators produce energy according to the requirements. [1]

After lessons learned from the Fukushima 2011 disaster, many NPP operators and authorities around the world have started to adopt actions to improve safety of the plants. Regarding to this, in Finland the ability of a NPP facility to withstand various external threats such as resistance against earthquakes and flooding has been under continuous research since Fukushima. At both Olkiluoto and Loviisa plants, some modifications were required to improve safety regarding plant systems, equipment, structures and operating practices. As an example, engineering of modification to replace emergency diesel generators (EDGs) was started at Olkiluoto to essentially upgrade the reliability of on-site power supply in exceptional situations. [1]

1.2 Topic of the study

This is a Master of Science thesis that investigates performance requirements and related characteristics of an emergency diesel generating system (EDG system). In this study, the application of the EDG system is an on-site emergency power generation for a nuclear power plant (NPP). The EDG system's most important function is to supply electricity to the NPP's safety and control systems (safety auxiliaries) in case of regular power supply from an off-site grid fails and during other critical emergency events. The EDG systems are specifically intended to operate in an "island", meaning that they can be totally independent of any external source of electricity. In this mentioned role, the EDG systems are an essential part of the NPP's safety systems.

As a summary, the EDG system consists of a large diesel engine, a generator and various auxiliary systems as well as electrical instrumentation that are necessary for proper function of the entire EDG system. In this study, Wärtsilä's own product, Wärtsilä 32 engine type and its auxiliaries are used as a common reference basis because its technology is well suited to operate in challenging nuclear emergency applications like EDGs. These applications are required to have a high performance, which includes typically abilities such as a fast and reliable start, quick loading, large load step capability, and ability to withstand long periods in stand-by mode waiting for instant start-up signal. [2]

It should be mentioned that is not mandatorily required by nuclear regulations that diesel generator technology is the only suitable technology for on-site power supplies at NPPs. For example, gas turbine technology can also be considered for this purpose. However, the reason for typically selecting EDG systems as the predominant means of supplying this emergency power can be found by looking at the time requirement set for readiness to accept loads following loss of off-site power (LOOP) event. The EDG system can reliably match this required response time and output power even in varying operating conditions. In addition, diesel generators are widely accepted for this purpose due to their proven technology and availability. [3]

There are number of studies that focus on EDGs since they have been used as the on-site emergency power supplies in NPPs for several decades. These earlier studies are covering a wide range of EDG related topics. Many of them appear to have a similar purpose: to define nuclear power plant's coping capability with undesired emergency events such as LOOP and station black-out (SBO) by specifying the reliability and/or the performance of the EDGs in different situations. Also some studies concentrate specifically on determining the operating reliability of the EDGs by evaluating unplanned demand failures and unavailability through the real operating experience data gathered from different databases. For example, NSAC 108 (1986) "The Reliability of Emergency Diesel Generators at U.S. Nuclear Power Plants" represents one of the commonly known EDG reliability studies.

1.3 Research justification, aim and target audience

Wärtsilä's product was chosen as the main focus of this study because the author was employed by Wärtsilä, and Wärtsilä as the manufacturer of the nuclear applications for the EDG systems is naturally interested in their performance requirements. Also, the possibility of the expansion of the nuclear energy in a carbon constrained world necessitates safe and reliable nuclear power plants, in which the EDG systems play an important role.

The main goal of this master's thesis is to explore the major performance requirements of the EDG system. In addition, the aim is to provide a comprehensive introduction to this particular system and discussion of other EDG system related topics from a performance and operating point of view. Therefore, this study can act as a handbook or an introduction to the EDG system in particular for newcomers in nuclear business. However, more experienced engineers can also make use of the contents of this research. The overall purpose of this study is to improve understanding of the EDG system and its specific features, and thus support safer NPP systems.

Research question and objectives

The overarching research question that has guided this work towards achieving the above mentioned aims is: ***What are the most important performance requirements specific for the nuclear EDG system?***

In order to answer this question, the following research objectives are identified:

- Objective 1: provide insight into the role of the EDG system operating with the NPP and other safety systems;
- Objective 2: discuss the commonly utilized nuclear regulations, standards and guidelines applicable for the EDG system;
- Objective 3: determine the required performance of the EDG system;
- Objective 4: identify possible factors influencing the performance of the EDG system;
- Objective 5: provide overview of applicable qualification procedures of the EDG system.

Chapter 8 summarizes this thesis and provides some discussion and conclusions from different viewpoints in the light of the research objectives presented above.

1.4 Scope and limitations

The focus and scope in this study are mainly on technical aspects but also legislative perspective is included. The technical part encompasses a detailed view about the EDG system's design based on Wärtsilä's solutions, selected requirements and specific features. Additionally, a general knowledge about the NPP's safety systems is also provided. The technical side concern both mechanical and electrical domains of the EDG system. The mechanical domain includes the engine and its mechanical auxiliary systems, and the electrical domain covers the electrical and automation (E&A) system and the generator as the latter can be considered to be an electrical component in its entirety. The legislative part comprises an overview of applicable nuclear regulations and regulatory frameworks. In this study, nuclear regulations as well as applicable standards are presented by means of frameworks that Wärtsilä follows as an engine manufacturer and an application supplier in the nuclear industry.

Furthermore, relatively large emphasis has been given to the qualification matters and procedures related to the EDG system because they play an essential role when applications such as EDGs are qualified for nuclear service. Also certain EDG related topics are briefly examined such as environmental conditions and reliability matters as these are strongly connected to the EDG system's ability to perform its intended functions reliably without interruptions. Figure 1 below shows an overview of boundaries of the EDG system and its related equipment.

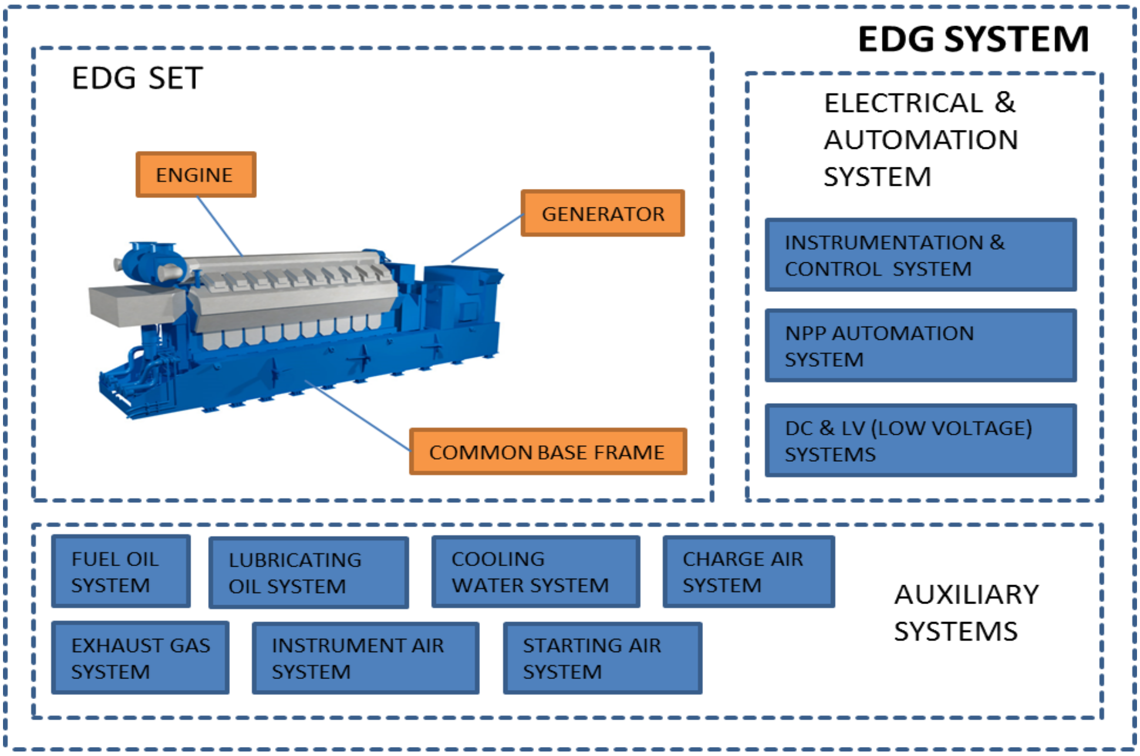

Figure 1: Overview of the EDG system and related equipment.

Due to length constraints for this study and multifaceted research subject, some of the topics initially planned to be included in the scope were omitted or depth of examination became perfunctory. Narrowing of the scope was done especially in Chapter 6, where only some specific features and requirements of the EDG system's components were selected for deeper analysis. Another initial aim was to make a comprehensive comparison between the nuclear EDG system and the non-nuclear industrial/conventional diesel power plant (base load DG-set application), but also due to abovementioned reasons this particular comparison is excluded from this study.

1.5 Research methods

For the most part, this master's thesis is a literature review based on the information that has been gathered mainly from applicable standardization as well as from Wärtsilä's internal and public documents. Other sources that have been utilized to produce this study include written literature such as books and scientific research studies (available in printed or/and online format) that deal with nuclear energy production, and fundamentals of diesel engine and generator technologies. Moreover, various informal discussions with Wärtsilä's expert engineers were carried out to fill the gaps in knowledge for instance in nuclear regulations, frameworks, mechanical and electrical domain, qualification etc. These discussions have also informed some of the drawings and tables presented in this thesis. This study does not include any experimental parts or calculations based on self-made measures.

1.6 Wärtsilä in brief

This master's thesis is written for Wärtsilä Finland Oy that is a part of Wärtsilä Corporation. Wärtsilä is a global leader in complete lifecycle power solutions for the marine and energy markets. By emphasizing technological innovation and total efficiency, Wärtsilä maximizes the environmental and economic performance of the vessels and power plants of its customers. In 2013, Wärtsilä's net sales totalled 4,7 billion euros with approximately 18,700 employees globally. The company has operations in over 200 locations in nearly 70 countries around the world. Wärtsilä is listed on the NASDAQ OMX Helsinki Exchanges, Finland. [4]

Wärtsilä Power Plants Solutions

Wärtsilä is the 4th-largest supplier of gas and liquid power plants in the world with a total installed capacity of 53 GW. Wärtsilä supplies modern, environmentally advanced, highly efficient and dynamic power plants that allow maximum integration of intermittent renewable power generation. Wärtsilä's power plant portfolio consists of multi-fuel power plants, including base load generation, peaking and load following operation, as well as dynamic system balancing and ultra-fast grid reserve. Power range can be tailored to meet customer needs from 2 MW to above 600 MW. Wärtsilä's services cover basic equipment delivery to comprehensive engineering, procurement and construction (EPC) solutions, and from spare parts supply to full operation and maintenance agreements. Figure 2 below shows Wärtsilä power plants product portfolio with optimal load profiles in 2013. [5, 6]

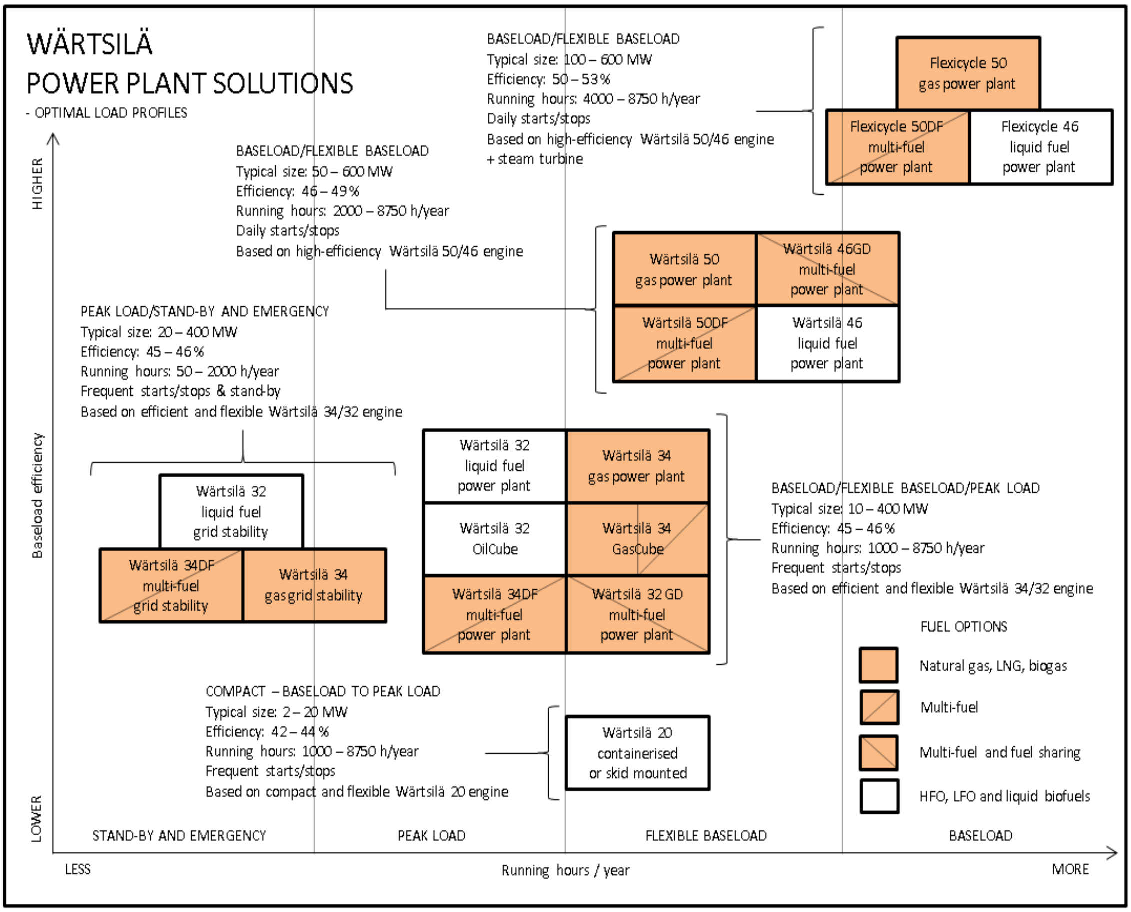

Figure 2: Wärtsilä power plant solutions with optimal load profiles. [6]

1.7 Structure of the study

The structure of this thesis is organized as follows:

- Chapter 1 has presented context for the thesis work and defined the research question and objectives. It has also delineated the scope and limitations, and described the audience. In addition, a brief summary of Wärtsilä's power plant business and product portfolio was presented in this chapter;
- Chapter 2 describes generally major safety systems of a conventional NPP and illustrates a role of the EDG system functioning together with the NPP;
- Chapter 3 provides an overview of EDG related nuclear regulations, regulatory frameworks and applicable standards that set requirements and offers guidance for example for the design and qualification aspects applied to the EDG;

- Chapter 4 describes the EDG system in detail so that all its main components and supporting auxiliary systems including their main functions are explained comprehensively to give basis for better understanding of applicable requirements and the EDG system's performance and operation;
- Chapter 5 examines the major performance related requirements and functionality of the EDG system. This chapter is concentrating for example on the EDG system's fundamental safety functions, starting and loading conditions, operating ratings and limit values etc.;
- Chapter 6 focuses to analyze selected components and systems highlighted from the EDG system. In this chapter, certain features and requirements of the engine and fuel oil system are studied;
- Chapter 7 examines the main qualification procedures that aim to qualify the EDG system into real nuclear service. Safety grading, testing and environmental qualification methods are in the center of this chapter. In addition to these, certain EDG related topics such as environmental conditions (ambient conditions at the NPP/EDG site, extreme weather etc.), a design service life as well as reliability aspects are shortly discussed within this chapter;
- Chapter 8 concludes the thesis by summarizing it, presenting main findings and answering to the research question in the light of the research objectives presented in Chapter 1.

2 NUCLEAR POWER PLANT SAFETY SYSTEMS

2.1 Overview

This chapter mainly focuses to explain the role of the EDG system functioning as part of a nuclear power plant (NPP). In this chapter, the NPP safety systems, defense in depth concept and design principles that are applied to these safety systems are introduced in general level. In addition, some identified design basis (emergency) events (DBEs), the on-site emergency power supply and arrangement with EDGs (NPP layout and locations of EDGs) are illustrated commonly inside this chapter.

2.2 Nuclear power plant safety systems

A nuclear power plant (NPP) is equipped with various safety systems for preventing possible failure situations and accidents. The ultimate safety function for all of safety systems is to ensure that a reactor core will remain undamaged during and after an accident or a failure event or at least to limit radioactive emissions from a damaged reactor core inside a containment building. All main safety systems of the NPP include various sub-systems or support systems, which usually can be considered as safety systems in general as well. The major and vital safety systems and their safety functions of a light water reactor (LWR) type NPP are summarized in the following Table 1. The LWR type reactor uses ordinary water as coolant, and it can be either a pressurized water reactor (PWR) or a boiling water reactor (BWR). For example, Loviisa NPP reactors are of a PWR type and Olkiluoto NPP reactors are of a BWR type. [7, 8, 9]

Table 1: Summary of main safety systems and associated safety functions of light water reactor (LWR) type NPP. [9]

Safety function	Safety system
Safe shutdown of reactor and maintaining it in subcritical state	Scram trip system of reactor, Boron supply system
Decay heat removal from reactor after shut-down and conducting decay heat to ultimate heat sink (i.e. sea) in normal operating conditions and during emergency situations	Emergency cooling systems of reactor, Decay heat removal systems and related support systems in cooling system chain
Ensuring undamaged condition of reactor containment building and preventing diffusion of radioactive emissions	Containment building of reactor, Isolation- and water sprinkler systems, Process systems for handling burning gases inside containment building, Suction ventilation and exhaust systems with filtration
Ensuring electricity supply to plant’s safety auxiliaries, their related equipment and sub-systems	Emergency electricity supply systems, Emergency diesel generating systems (EDGs) or battery back-up systems
Securing undamaged condition of primary heat circuit	Overpressure protection system

Each NPP safety system and its related equipment are designed so that they are categorized into certain safety classes depending on the significance and the purpose of the safety function in question. The principles of the safety classification (safety grading) and how it is applied to the EDG system are described in Section 7.2 of this study. [9]

2.3 Defence in depth concept

The application of the concept of defence in depth represents the primary means of preventing accidents in the NPPs and mitigating the consequences of possibly occurring accidents. This is done throughout design and operation that provides protection against expected operational occurrences and accidents, including those that result from equipment failure or human included events with the NPP, and against consequences of events that originate outside the NPP. The defence in depth concept is applied to all safety related activities (organizational, behavioral or design related), and in any NPP operation states (full power, low power or various shutdown states). [10]

The concept of defence in depth consists of a hierarchical deployment of different levels of equipment and procedures in order to maintain the effectiveness of physical barriers placed between a radiation source or radioactive materials and workers, members of the public or the environment, in operational states and, for some barriers, in accident conditions. The main objectives of defence in depth are to compensate for potential human and component failures, to maintain the effectiveness of the barriers by preventing damage to the facility and to the barriers themselves, and to protect the public and environment from harm in the event that these barriers are not fully effective. The independence of different levels is an essential element in achieving the main objectives of the concept. The concept of defence in depth basically forms the core for other design principles on the NPP level (see Section 2.4). Based on SSR-2/1 and INSAG-10 safety standards, there are five levels of defence in depth. In case one level fail, the subsequent level comes into force. The objectives of each level and essential means of achieving them are presented in Table 2 below. [10, 11]

Table 2: Levels of defence in depth with objectives and essential means. [11]

Levels of defence in depth	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

2.4 Design principles

There are several essential design principles that must be applied to ensure that all NPP safety systems, including emergency power supply systems such as EDG systems, perform their required safety functions reliably. These design principles may be applicable on a system, a sub-system or a component level. All design principles are based on the criteria that originate from a customer (NPP operator, constructor or licensee), a nuclear regulator (authority) or from applicable standards. Additionally, the design of NPP safety systems can be based on experience or probabilistic statistics in conformance with the following design principles: [9, 12]

- Redundancy;
- Separation;
- Diversification/diversity;
- Simplicity;
- Fail safe;
- Independency.

Redundancy
According to redundancy principle, the safety systems are divided into several subsystems, which create back-up systems (substitutes) for each other including same safety function. The so called failure criterion of N+2 can be applied for example to protection systems that automatically control functions of the safety system. In the case of the automatic protection system, it can be equipped four parallel devices with similar functions, and if two of them fail, remaining two devices can still perform required functions such as control and start of related safety system. For example, N+2 redundancy principle has been applied in NPPs in Finland and currently in Generation III NPPs around the world. Sometimes, if it’s allowed, N+1 failure criterion can be applied to lower level safety systems since the safety system must perform its safety function even if any single device is unable to function (single failure proof). As an example, older NPPs around the world may only be equipped with N+1 principle. However, increasing redundancy necessarily doesn’t improve reliability. In fact, it actually can reduce reliability of a safety system because of more complex overall design. [9, 12]

Separation
The separation principle comprises a combination of a physical and a functional separation. The physical separation means that parallel sub-systems or components of the safety systems are physically placed into separate spaces. In exceptional cases, these subsystems may be placed so that space (distance) between systems or components is adequate or it’s required to install protective structures between them. The purpose of functional separation is to avoid mutual interference of parallel sub-systems or components. [9, 12]

Diversification/diversity
The principle of diversification (diversity) is used for improving reliability and avoiding possible common cause failures (CCF) to happen in the safety systems. For example, two safety systems that have similar safety functions can be applied with diversification principle so that operating principles in both systems are different and completely independent. Generally, the automation- and electricity systems of the NPP are designed based on the diversification principle. [9, 12]

Simplicity
The main idea of the simplicity principle is that a safety system shall be designed to be as simple as possible in order to achieve sufficient reliability. A non-safety related (NSR) system that doesn't perform any safety functions may be complex, but it must not disturb or interfere the function of a safety related (SR) system. The level of simplicity in the design affects also to qualification of nuclear safety systems; a simpler safety system is easier to qualify than a complex one. [9, 12]

Fail safe
The purpose of the fail safe principle is to ensure that a component or a system gets into the most beneficial mode if it failures, and does not cause harm to other systems when experiencing failure situation. If this most beneficial mode is not found or it's out of reach, then aim is to find as such favorable mode as possible so that a component or a system in question can be restored into service condition easily. The fail safe principle is used for example in the design of the reactor protection system that initiates the NPP's safety systems when necessary. [9, 12]

Independency
Possible failures and hazards (single failures, CCFs, consequential failures, external hazards etc.) are taken into account in the design of the NPP's safety systems. These failures shall be prevented to happen. The ultimate goal is to achieve the independency by means of all design principles described above. One of main purposes of the independency principle is to ensure that a higher level system is not dependent on a lower level safety system, or parallel safety systems are not dependent on each other (e.g. another EDG). [9, 12]

2.5 Identified emergency events

Some of the most crucial identified design basis emergency events or accidents for a LWR type NPP are listed below:

- Loss of Off-site Power/Loss of AC Electrical Power (LOOP);
- Loss of Coolant Accident (LOCA);
- Steam Line Breaking (SLB);

- Station Blackout (SBO).

The loss of off-site power (LOOP) is an emergency event where AC electrical power to the NPP from the off-site grid is lost for some reason. Typically LWR type NPPs are furnished with EDGs just for this purpose; preventing electricity unavailability caused by LOOP. The loss of coolant accident (LOCA) results from water leakage from primary cooling circuit of the reactor due to failure (rupture) of a large coolant pipe. The steam line breaking (SLB) is an accident that signifies steam loss from a secondary circuit of the reactor.

The station blackout (SBO) is the one of the most severe design basis events (DBEs) that may lead to a reactor core melt. The SBO event occurs when all off-site and on-site alternative current (AC) power sources including emergency power systems such as EDGs are simultaneously lost. As an example, Fukushima Daichi NPP accident in 2011 was an extreme result of extended SBO event. It was caused by two consecutive natural disasters, earthquake and tsunami, which disabled both off-site and on-site power sources of the NPP (including EDGs) and eventually situation led to the reactor core melt and caused dangerous radioactive emissions into environment. [7, 8, 9, 13, 14]

2.6 NPP emergency power supply with EDGs

Generally, a NPP is connected to a country electricity grid through three or more off-site power lines, where one of them is the main power line. In all operation conditions, power for the NPP’s auxiliaries is taken from the off-site grid or from the NPP’s main generator. EDGs installed must be available at any time, and they must follow required redundancy principle (failure criterion N+2 or N+1). In normal operation of the plant, EDGs are in stand-by mode waiting for start-up command. Depending on the reactor type and design, one EDG can be under maintenance for a few days as specified in the NPP operation instructions. Major overhauls of EDGs take place during a periodical maintenance break of the NPP (e.g. once per year for LWR type NPP, and for EPR type NPP every 18 to 24 months). Typically EDGs are tested one or two times per month when they are run for about 1 – 4 hours, and several times per year EDGs may be tested to run for up to 24 hours to ensure that they and related auxiliary systems as well as other necessary equipment would function as required to be ready for LOOP. [7, 15]

Typically a single reactor is equipped with two to four EDGs depending mainly on age of the NPP and national regulations. Also the NPP type (PWR, BWR, CANDU etc.) and overall design requirements have influence how many EDGs are delivered and installed in the NPP. Each EDG system is physically separated and their control systems are isolated meaning that EDGs are not relying in common interconnection between each other. The ultimate premise in nuclear power is that emergency power supply equipment must be at least single failure-proof (N+1 criterion), which should guarantee that at least one train of the emergency equipment will function. In most cases each EDG is provided with own individual emergency power supply train, but in some cases depending on the reactor design, EDGs can be connected to NPP's emergency switchgear even by four redundant trains. [7, 9, 16, 17]

Example: Loviisa Nuclear Power Plant
Loviisa NPP in Finland is connected to the national power grid by two 440 kV power lines and by one 110 kV power line. Generated electricity from the NPP is transmitted to the off-site grid via a 400 kV switchyard. Both reactor units of the NPP are equipped with four EDGs, from which only one EDG has enough capacity to produce needed electricity for the NPP's safety auxiliaries. The plant also has direct connection to Ahvenkoski hydroelectric power station that provides secure stand-by power supply in case of long-term off-site grid unavailability. Additionally, one stand-by diesel generating set (Wärtsilä 20V32) can be connected to both reactor units, but it doesn't have safety function responsibility (non-safety classified). Direct current (DC) supply to the NPP's measurement- and automation systems in case of emergencies is secured by batteries, which in turn are supplied through AC system. The following Figure 3 illustrates how AC stand-by power supply is arranged in Loviisa NPP. [9, 12]

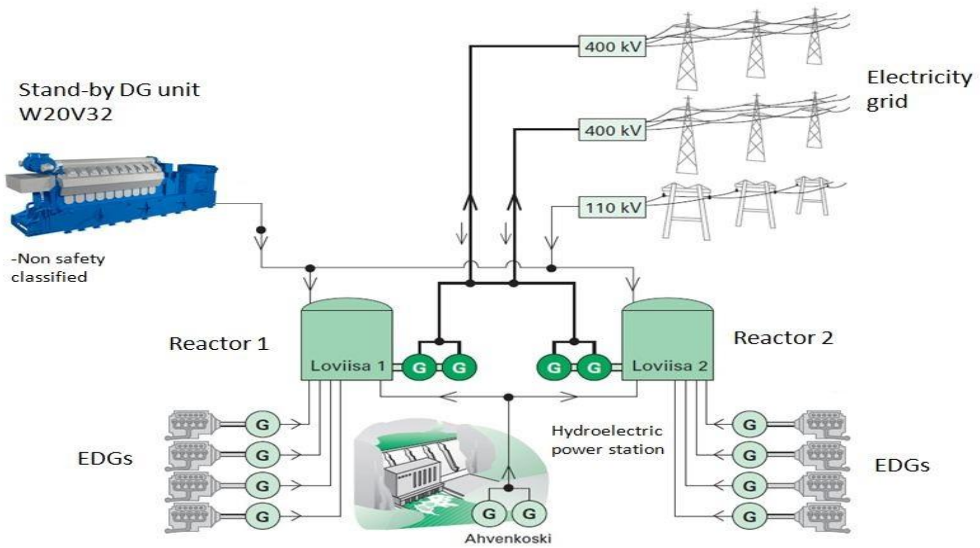

Figure 3: Stand-by power supply arrangement of Loviisa NPP in Finland (modified drawing). [9, 12]

2.7 NPP emergency operation with EDGs

In the case where the reactor protection system detects certain abnormal conditions, the NPP will experience an immediate shutdown sequence, and EDGs are started-up automatically to supply emergency power for the NPP's safety auxiliaries. Typically emergency operation of the EDGs is initiated by the NPP's control system from the main control room (MCR). The EDGs are feeding emergency power through an emergency switchgear (special safety electrical distribution panels), which in turn supply power in priority for cooling and circulation pumps to ensure that decay heat from the reactor after shutdown is removed continuously to a ultimate heat sink in a safe manner. In addition to this, the EDGs are feeding e.g. fire detection systems, emergency lighting, control power batteries and other safety related power loads needed to maintain the plant in safe condition. During a LOOP event, the NPP is operating as an island, wherein EDGs will supply stand-by power as long as necessary such that the off-site power connection is re-built. The emergency stand-by power may have to be delivered to the NPP for duration of several days meaning that the EDGs must be able to run continuously this time without local attendance. [7, 9, 12]

Furthermore, the NPP can be furnished with a separate station black out unit (SBO) unit that is either a non-safety classified or has a lower safety classification than the EDG system has. The SBO unit owns certain functional and physical diversity, and typically its rated output power is lower than the EDG has. The SBO unit is always started manually to supply power for specified safety systems in the NPP. [7, 9, 12]

2.8 NPP layout and location of EDGs

Almost always NPP sites differ from each other in design and environmental requirements. Therefore it’s not precisely set where EDGs should be placed in the NPP area. There are two locations where the EDGs can be placed; either outside or inside the reactor building. As an example, NPPs in United States typically houses EDGs outside, where they are typically placed in a separate building located near the reactor facility. Benefit of this arrangement is that the staff of the NPP can easily access in the EDG building whenever it’s necessary (e.g. for maintenance or surveillance purposes). In case the EDGs are located inside the reactor building, there is a bunkered room reserved specifically for them and related auxiliary systems. [18]

Normally EDG buildings are steel-reinforced concrete structures or similar design with concrete walls. Like the reactor building, EDG building is designed to withstand impacts of natural disasters such as floods, earthquakes, hurricanes and tornadoes, which are specific to region of the NPP site. However, often auxiliary systems of the EDG are located outdoors in vicinity of the EDG building and therefore some components (e.g. tanks and vessels) may be exposed to these natural disasters more easily than the actual EDG set. The current trend is that the reactor building itself often is designed to withstand even impact of an airplane crash. Environmental conditions (e.g. natural phenomena) that may affect the EDG system’s equipment and performance are examined later in Section 7.6.1. Locations of EDG buildings can be seen in Figure 4 below, which shows a general layout of European Pressurized Reactor (EPR) type NPP. [18]

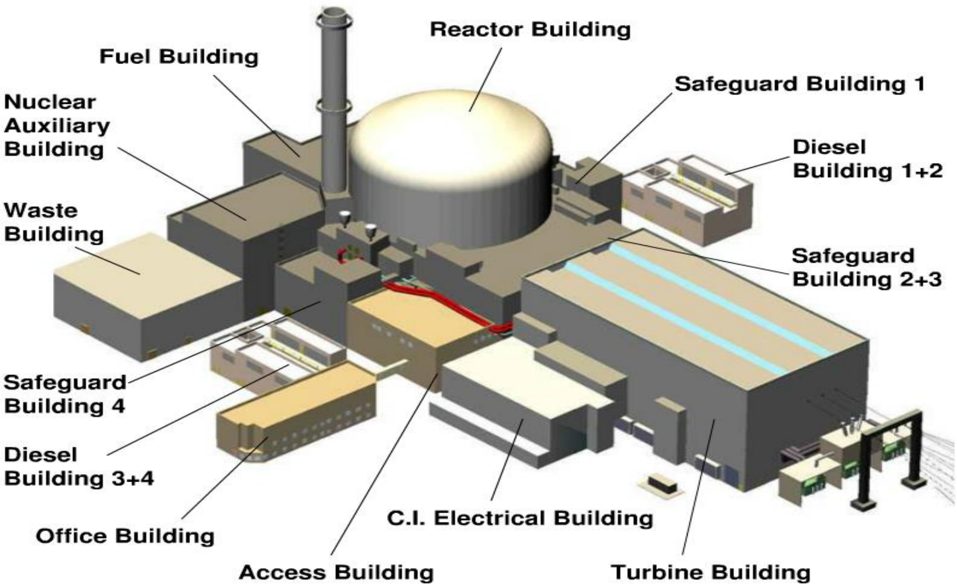

Figure 4: General layout of European Pressurized Reactor (EPR) type NPP. [19]

3 REGULATIONS AND STANDARDS

3.1 Overview

This chapter gives an overview of the regulatory framework that a nuclear application manufacturer or supplier (e.g. Wärtsilä) typically follows in order to be an actor in the field of nuclear application business. To clarify this framework structure and concept as well as sources of nuclear requirements, Finnish regulatory framework and important authority facets, International Atomic Energy Agency (IAEA), and Finnish Radiation and Nuclear Safety Authority (STUK) are introduced in this chapter. Also a brief comparison of the U.S., Finnish and German regulatory frameworks is presented providing more perspective to this subject.

Regarding to applicable standards and guides that apply to the EDG system, this chapter highlights some of the relevant standard families and introduces two commonly known technical standards defining nuclear EDG specific criteria known as KTA 3702 and IEEE 387.

3.2 Regulatory framework

Requirements applicable to nuclear applications, originate from various sources, which are:

- Government;
- Authority (IAEA, Regulatory body);
- Customer (NPP owner or operator, licensee holder); and
- Manufacturer (nuclear application supplier, e.g. Wärtsilä).

In general, the government sets statutory and regulatory requirements in the form of codes, standards and norms. The international nuclear authority (International Atomic Energy Agency, IAEA), provides guidelines and recommendations to the national level authority. The national nuclear authority (regulatory body, e.g. STUK in Finland) grants license requirements, gives recommendations and instructs the nuclear application supplier how to fulfill nuclear safety regulations. The customer sets contractual, technical and project management system requirements. These requirements are defined for instance in contractual terms as well as, technical specifications and drawings. Figure 5 below illustrates the structure of the regulatory framework that Wärtsilä as an example follows internationally and nationally. [20, 21, 22]

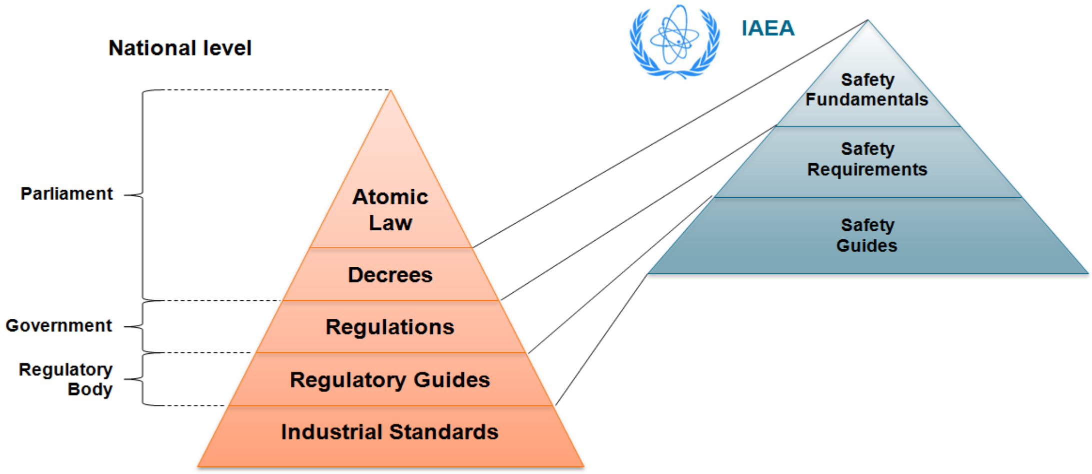

Figure 5: Structure of regulatory frameworks (international and national) that a nuclear application manufacturer (e.g. Wärtsilä) shall follow. [20]

3.2.1 Finnish regulatory framework

In Finland, the utilization of nuclear energy and its surveillance are dictated by the national legislation and regulations. Finnish nuclear legislation and safety regulations take into account international agreements (conventions) and guidelines (recommendations). The most important sources of law for Finnish nuclear energy legislation are the Nuclear Energy Act (990/1987) and the Nuclear Energy Decree (161/1988). In addition, general safety regulations verified by Finnish Government have important input to nuclear legislation, called as decisions made by the Council of State. [9, 23, 24, 25]

IAEA

Finnish nuclear agreements and guidelines are generally developed in the guidance of the International Atomic Energy Agency (IAEA), which operate under the United Nations. One main function of the IAEA is to prepare and develop instructions and recommendations related to nuclear and radiation safety. The IAEA's hierarchy of statutes consists of the following instruction levels: [9, 24, 25, 26]

- Safety Fundamentals;
- Safety Requirements;
- Safety Guides;
- Safety Reports.

The highest level of the hierarchy is comprised by the 'Safety Fundamentals'-documents, which describe nuclear safety related principles and basic targets. The 'Safety Requirements'-documents in turn define requirements in order to achieve these safety targets. The 'Safety Guides'-documents recommend methods and procedures for fulfilling the safety requirements whereas the ‘Safety Reports’-documents introduce good practices to perform these methods. [9, 24, 25, 26]

STUK

Finnish Radiation and Nuclear Safety Authority (STUK) is the nuclear regulatory body, which operate under the Ministry of Social Affairs and Health. STUK is responsible for the supervision of nuclear safety and regulates the use of NPPs and radiation in Finland. As defined in the Finnish Nuclear Energy Act, STUK has the authority to regulate the safety of nuclear energy utilization in Finland. The main duties of STUK are: [9]

- Preparation and publication of national regulatory guides on nuclear safety (YVL-Guides);
- Safety evaluation of the NPP construction and related applications;
- Inspections to verify the safety state of the facility and the compliance with license conditions over the NPP lifetime;
- Inspections on nuclear waste management and nuclear material safeguards; and
- To ensure that nuclear power is produced in a safe manner.

3.2.2 Regulatory framework comparison

IAEA states that national regulatory bodies (like STUK in Finland) should preferably have a reactive approach. This means that a nuclear installation designer or manufacturer proposes specific technical and quality solutions, which may deviate from solutions that regulatory body recommends in regulatory guides (for example in YVL-Guides). The objective of this approach is that proposed solutions will be reviewed, commented, and eventually approved by regulatory body as long as they fulfil the required level of nuclear safety. Ideally the requirements stated in the guidelines define safety boundaries within which the nuclear installation manufacturer has an opportunity to optimize the design. [9, 25]

Internationally Wärtsilä as a nuclear equipment supplier complies with regulatory frameworks of countries, which have signed the Joint Protocol Relating to the Application of Vienna Convention and Paris Convention (issued on 21 September 1988 and put into force on 27 April 1992). All national regulatory frameworks (including that of Finland) are following more or less the same pattern. Requirements coming from the customer will take account of the national regulatory framework and possible additional requirements. Therefore, nuclear projects often look similar, but are not identical. Figure 6 below illustrates how these national regulatory frameworks may differ from each other. [20, 22]

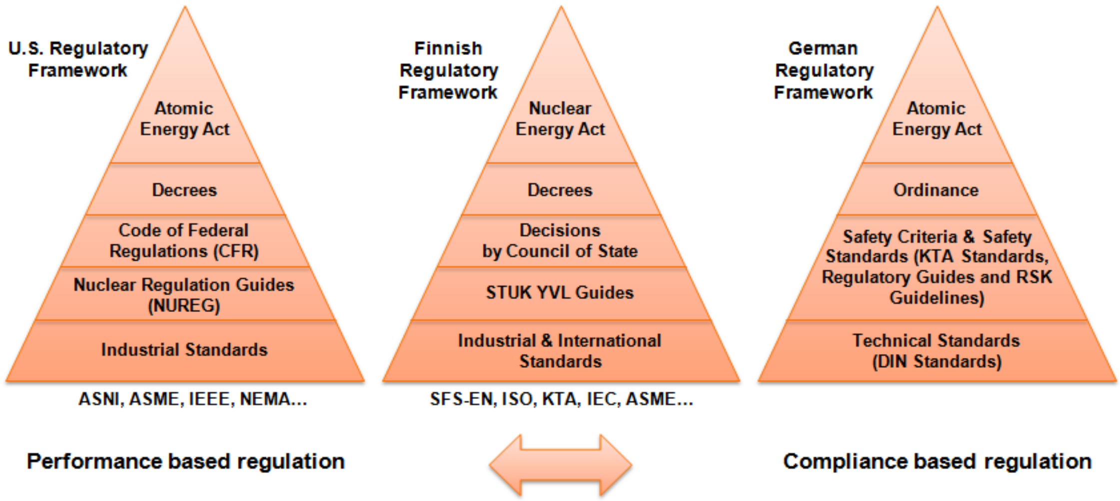

Figure 6: Comparison of the U.S, Finnish and German regulatory frameworks. [20]

As an example, the regulatory framework of the United States is performance-based. In other words laws, regulations and guidelines set the goal (e.g. requirements for proper nuclear safety) and it is up to the utility to decide the manner in which shall be used to achieve the goal. The aim of this approach is more like continual improvement. The German regulatory framework in turn represents a different kind of approach that is compliance-based. In this approach, laws, regulations and guides set the goal as well as the means to achieve it. The Finnish regulatory framework has features from both performance- and compliance-based approaches. [20, 22]

3.3 EDG applicable standards and guides

As the nuclear EDG system consists of various mechanical and electrical components, there are a number of specific standards, codes and guidelines at the national and international levels detailing instructions on the way in which the required technical, seismic and environmental performance as well as required nuclear reliability and safety can be achieved. The standardization and norms that will be used as guidance in the design and manufacturing etc. are always determined by the customer, which in turn has to follow the national and international nuclear legislation.

These applicable standards can roughly be divided into two categories: industrial standards and nuclear specific standards. Industrial standards are commonly accepted requirements, which are followed by the members of an industry, whereas nuclear specific standards are developed especially to provide the principal criteria of design, qualification and testing requirements for nuclear power plants and nuclear applications. Table 3 below gathers some of the important standard families that the nuclear application manufacturer complies with typically. This particular table also shows examples of standards that may be applied for the electrical and mechanical design as well as for qualifying the EDG system. [27]

Table 3: Relevant standard families, standards and regulatory guides applicable for nuclear EDG system. [12]

Standard family	**Industrial or Nuclear specific**	**Electrical or Mechanical domain**
KTA: Kerntechnischer Ausschus, Nuclear Safety Standard Commission	Nuclear specific: KTA 3701: General Requirements for the Electrical Power Supply in Nuclear Power Plants) KTA 3702: Emergency Power Generating Facilities with Diesel-Generator Units in Nuclear Power Plants	Electrical, Mechanical
IEEE: Institute of Electrical and Electronics Engineers	Nuclear specific: IEEE 308: Standard Criteria for Class 1E Power Systems for Nuclear Power Generating Stations IEEE 387: Standard Criteria for Diesel-Generator Units Applied as Standby Power Supplies for Nuclear Power Generating Stations	Electrical, Mechanical
IEC: International Electrotechnical Commission	Industrial: IEC 60034: Rotating Electrical Machines Nuclear specific: IEC 60709: Nuclear Power Plants - Instrumentation and Control Systems Important to Safety - Separation	Electrical
EN: European Standards	Industrial: EN 60204-1: Safety of Machinery - Electrical Equipment of Machines - General Requirements	Electrical, Mechanical
ISO: International Organization of Standardization	Industrial: ISO 15550: Internal Combustion Engines - Determination and Method for the Measurement of Engine Power - General Requirements	Mechanical
YVL: Ydinvoimalaitosohjeet, Finnish YVL Guides, Säteilyturvakeskus	Nuclear specific: YVL E.10: Emergency Power Supplies of a Nuclear Facility	Electrical, Mechanical
NRC-RG: U.S. Nuclear Regulatory Commission - Regulatory Guides	Nuclear specific: NRC-RG 1.9: Application and Testing of Safety-Related Diesel Generators in Nuclear Power Plants	Electrical, Mechanical

3.3.1 Technical standards KTA 3702 and IEEE 387

From the previous Table 3, two technical standards, KTA 3702 (2000) and IEEE 387 (1995), can be highlighted and introduced briefly. Both standards define nuclear specific criteria regarding to the EDG system. They also include many references to other nuclear specific standards, but they are not introduced in this study in the same extent.

KTA 3702 (2000): Emergency Power Generating Facilities with Diesel-Generator Units in Nuclear Power Plants

KTA 3702 is German safety standard that applies to emergency power generating facilities with diesel-generator units in stationary nuclear power plants. The standard covers detailed design, documentation and testing requirements. It includes technical specifications and design parameters, which are exemplified by various tables and appendices. The boundaries of the scope encompass a diesel-generator unit, most of auxiliary systems and instrumentation and control (I&C) system. The scope excludes some of EDG related systems such as air conditioning, external cooling system, emergency power switchgear, power supply for auxiliary drives etc. Figure 7 below shows the scope of the emergency power generating facility defined in KTA 3702 standard. [17]

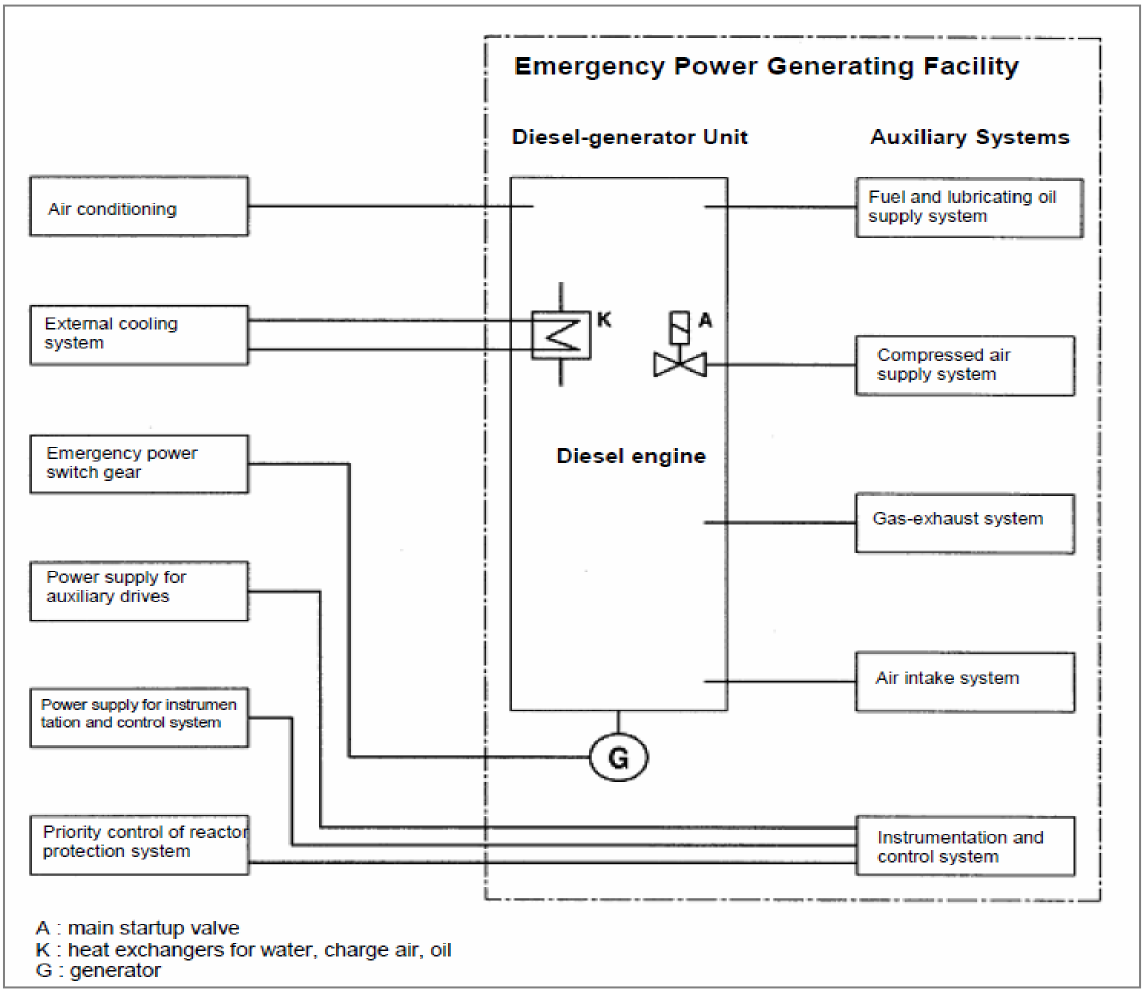

Figure 7: Scope of emergency power generating facility in KTA 3702 standard. [17]

IEEE 387 (1995): Standard Criteria for Diesel-Generator Units Applied as Standby Power Supplies for Nuclear Power Generating Stations

IEEE 387 (1995) is U.S. standard that describes the criteria for the application and testing of diesel-generator units as Class 1E (safety related class) standby power supplies in nuclear power generating stations. The principal design requirements, factory production testing, qualification requirements, site testing and documentation are covered in the standard. The boundaries of the scope encompass a diesel-generator unit, auxiliary systems, and a local control protection and surveillance system. Inside the scope are also AC and DC distribution systems that can be associated with the engine, the generator and their auxiliary equipment. The scope excludes equipment such as fuel oil storage and supply system, diesel-generator unit enclosure and foundations, fire protection system etc. However, main interfaces with the equipment and systems that are outside of the scope are explained in some extend in this standard. [28]

Compared to KTA 3702 standard, the scope of the design criteria in IEEE 387 standard is wider. Moreover, it seems that IEEE 387 standard itself provides more freedom to the nuclear application manufacturer to decide practices in design for achieving required and acceptable levels of performance and safety. The scope and boundaries of the Class 1E diesel-generator unit is shown in Figure 8 below. [17, 28]

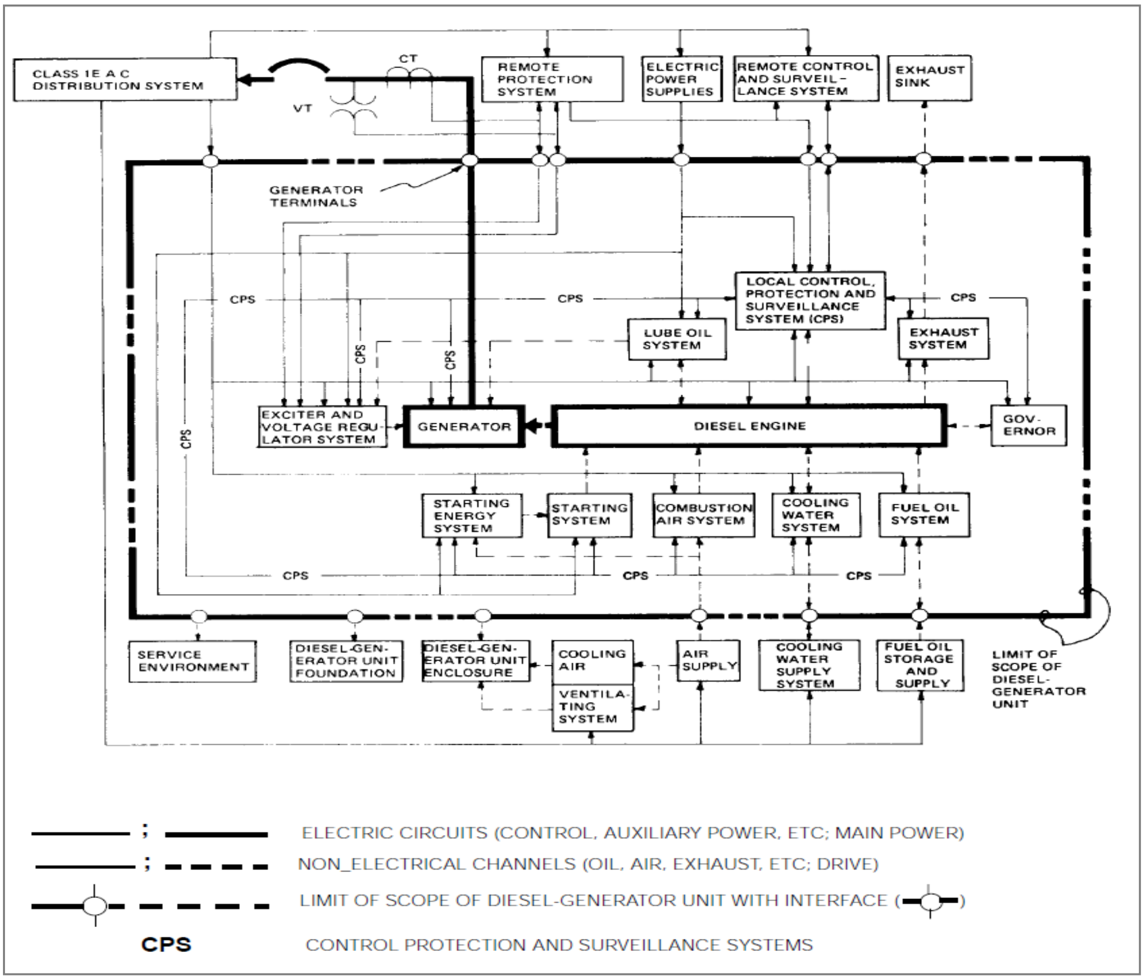

Figure 8: Scope of Class 1E diesel-generator unit in IEEE 387 standard. [28]

3.3.2 Finnish YVL-Guides

Finnish YVL-Guides include definitions and requirements of minimum levels of safety and surveillance procedures for NPPs in Finland. In principle, these guidelines do not change the decisions of STUK made prior to the publication of the Guides; however often YVL-Guides form the actual regulatory system. YVL-Guides are not legally binding but they are intended to give guidance to designer and operators of nuclear installations. Their purpose is also to act as a standard of reference in inspections and reviews for regulatory inspectors. The regulatory system allows deviations from the requirements of YVL-Guides, if the NPP license holder or a nuclear installation manufacturer presents an acceptable solution by which the required safety level stated in the YVL-Guides is attained. [9, 24, 25]

New YVL-Guides came into effect on 1st of December 2013. These new guides will be applied as such to all new nuclear facilities. The requirements of the new guides are applied also to existing nuclear facilities and facilities under construction. A total of 44 new YVL-Guides are categorized as follows: [9, 24, 25]

- Group A: Safety management of a nuclear facility (YVL A.1 – A.12) ;
- Group B: Plant and system design (YVL B.1 – B.8);
- Group C: Radiation safety of a nuclear facility and environment (YVL C.1 – C.6);
- Group D: Nuclear materials and waste (YVL D.1 – D.6);
- Group E: Structures and equipment of a nuclear facility (YVL E.1 – E.12).

From the list above, Group E includes one specific YVL-Guide that concerns EDGs particularly. This YVL-Guide E.10 – Emergency power supplies of a nuclear facility, defines requirements and provides instructions for the design, manufacturing, installation work, commissioning, maintenance and condition monitoring. The guide also describes methods of surveillance that STUK follows when supervising compliance of these requirements. This E.10 guide is applied to emergency power supplies that belong to safety class 2 and 3. According to YVL E.10, the EDG system as a whole belongs to safety class 2, which is the second highest safety class. For EDG related design requirements, the guide refers to additional YVL-Guides and KTA 3702 standard as follows: [15, 24, 25]

- KTA 3702 (Diesel generator unit);
- YVL B.1 (System design);
- YVL E.7 (Electrical and Automation equipment);
- YVL E.6, YVL B.7 and YVL B.8 (Buildings, constructions and structures);
- YVL E.3, YVL E.8, YVL E.9 and YVL E.11 (Piping and pressure equipment).

4 EMERGENCY DIESEL GENERATING SYSTEM (EDG SYSTEM)

4.1 Overview

The aim of this chapter is to provide a comprehensive technical knowledge base for a nuclear emergency diesel generating system, its related equipment and their functions. The following descriptions of different systems and components are mainly based on Wärtsilä's products and definitions. Other EDG applicable arrangements that have been realized commonly in nuclear power plants are considered only on a general level in this chapter.

An emergency diesel generating system (EDG system) comprises the emergency diesel generating set (EDG set) and its auxiliary systems. Wärtsilä 32 EDG set consists of the Wärtsilä 32 engine, a generator and a common base frame. The engine is a reciprocating medium speed diesel engine and it works as a prime mover. It's connected to the generator with a flexible coupling. Depending on the installation at issue, the generator produces either low (< 1000 VAC) or medium (> 1000 VAC) voltage electricity. The engine and the generator are fastened to the common base frame that offers stable and vibration isolated platform for both.

Auxiliary systems connected to the EDG set ensure proper function and enables optimal performance of the EDG in any operation situation. Functions of these auxiliary systems is to provide the engine with fuel oil, lubricating oil, compressed air, cooling water, and charge air, in required quantity and quality, as well as to dispose exhaust gases from the engine. These auxiliary systems comprise various different mechanical components (pumps, valves, filters, tanks etc.) that are either mounted on the EDG set or are located outside the EDG set.

Besides mechanical equipment, the EDG system includes also electrical and automation (E&A) system. This system is used for monitoring, controlling and protection of operation of the EDG system without a continuous local attendance. In addition the purpose of the E&A-system is to act as a human machine interface (HMI) and provide operating power to the EDG system (house load) during operation and in stand-by mode. The E&A-system consists of various electrical components such as control panels, electrical cubicles and instrumentation (sensors, switches, actuators etc.) mounted on the EDG set and its auxiliary systems.

4.2 Emergency diesel generating set

4.2.1 Engine

The Wärtsilä 32 engine is a turbocharged, four-stroke, medium speed diesel engine with after-cooling and direct fuel injection. The engine is of a trunk piston type, and it's started with compressed air. The cylinder configuration of the engine design can be either In-line (L-type engine) or V-form (V-type engine). In V-type engines cylinders are located in two banks, A- and B- bank, whereas in-line engines have one cylinder bank. Number of cylinders varies from 6 to 20 depending on desired rated power output. Figure 9 below shows the assembly of Wärtsilä 20V32 diesel generating set. [29]

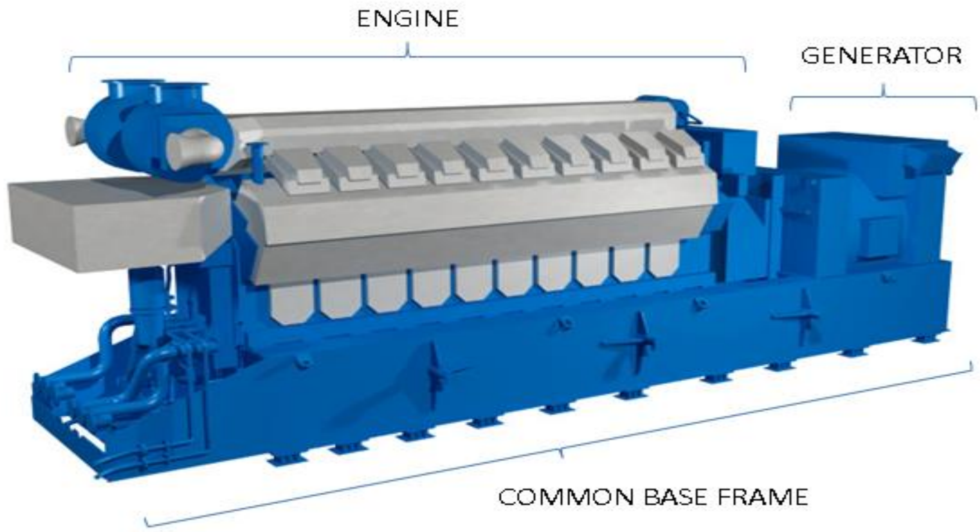

Figure 9: Wärtsilä 20V32 diesel generating set. [30]

4.2.1.1 4-stroke diesel engine combustion principle

The function of an internal combustion diesel engine is to convert chemical energy of liquid fuel into mechanical energy. A combustion process happens in cylinders, and it follows diesel cycle, which consists of four strokes: intake, compression, combustion and exhaust strokes. Diesel fuel is injected into cylinders at high-pressure by camshaft-operated pumps. Due to high temperature resulting from compression, fuel is ignited instantly. After a working phase, exhaust gas valves open and cylinders are emptied of exhaust gases. While pistons are in upper position, inlet valves open just before exhaust gas valves close, and cylinders are filled with air. [29, 31]

In Wärtsilä manufactured 4-stroke diesel engines the inlet valves close just before the piston reaches the bottom dead center (BDC). This method is called "Miller timing" and it reduces the work of combustion and combustion temperature which results higher engine efficiency and lower emissions. The combustion in the cylinders causes reciprocating movement of pistons that are connected to the engine crankshaft by connecting rods. This reciprocating movement eventually creates rotational movement of a crankshaft. For further applying of diesel engine combustion fundamentals, reference [29] is recommended. [29, 31]

4.2.1.2 Main characteristics of Wärtsilä 32 EDG engine

The Wärtsilä 32 engine for nuclear EDG application is designed for continuous operation at any load. Typical operation modes of the engine are stand-by and emergency mode (duty type based on Wärtsilä's definition). The rated speed of the engine is either 720 rpm or 750 rpm depending on electricity grid characteristics (50 Hz or 60 Hz). The engine consumes only high-quality light fuel oil (LFO). The nominal power output per cylinder is 500 kW when the EDG is connected to 50 Hz grid and 480 kW for 60 Hz grid. Allowed overload limit for the engine is 10 % above its rated power and overloading may be performed for 2 hours per every 24 hour period. Table 4 below summarizes the main characteristics of the Wärtsilä 32 EDG engine. [2, 29, 32]

Table 4: Main characteristics of Wärtsilä 32 EDG engine. [2, 29, 32]

Wärtsilä 32 EDG engine	
Available engine types (Number of cylinders and cylinder configuration V- or L-type)	6L, 8L, 9L, 12V, 16V, 20V
Cylinder bore	320 mm
Piston stroke	400 mm
Rotational direction	Clockwise (when facing driving end)
Rated speed	720 / 750 rpm
Mean piston speed	9.6 / 10 m/s
Mean effective pressure in cylinders	24.9 bar
Mechanical efficiency (compress ratio)	16.0:1
Output per cylinder (mechanical)	480 / 500 kW
Engine power range (mechanical)	2 880 – 10 000 kWm
Generating set power range (electrical)	2 780 – 9730 kWe
Typical duty type (Wärtsilä's definition)	Stand-by/emergency
Fuel	Light fuel oil (LFO)

4.2.1.3 Adjustment of engine power (de-rating)

The engine power can be adjusted due to difficult operating conditions (normally related to ambient conditions). The purpose of power adjustment (de-rating) is to protect the engine from harmful and unnecessary overloading. Standardized reference conditions for the power adjustment are defined in ISO 15550 (2002) standard, and additionally the engine manufacturer may use typical substitute reference conditions based on this standard. General methods for the engine power adjustment are described in ISO 3046-1 standard. The reference conditions are also used for calculating specific fuel oil consumption of the engine by means of power adjustment methods. Table 5 below summarizes typical substitute reference conditions and standardized reference conditions from ISO 15550 standard with value limits. [29, 33, 34]

Table 5: Standardized and typical substitute reference conditions for power adjustment and fuel oil consumption. [29, 33, 34]

Condition/parameter	**ISO 15550:2002 standard reference conditions**	**Typical substitute reference conditions**
	Value (min/max)	**Value (min/max)**
Total barometric pressure (p_r)	100 kPa (min)	100 kPa (min)
Ambient air (intake air) temperature (T_r)	298 K (25 °C) (max)	308 K (35 °C) (max)
Charge air coolant temperature, LT-circuit ($T_{cac,r}$)	298 K (25 °C) (max)	318 K (45 °C) (max)
Relative humidity (φ_r)	30 % (max)	-
Sum of exhaust gas back pressure and intake air pressure drop (Δp_r)	-	≤ 5 kPa

Relative humidity is not included in typical substitute conditions, but it may affect to the LT-charge air coolant temperature. The large amount of glycol in the cooling water typically degrades heat transfer properties of the engine, thus it needs to be taken into account when adjusting the engine power. Normally the power adjustment is applied to industrial graded engine applications (e.g. base load power plant engines) to fit operation parameters in prevailing site conditions, whereas power output of the EDG engine is taken into account already in early design phase (e.g. proper sizing). This topic is discussed more in Section 6.2.6. [29, 33, 34]

4.2.1.4 Main components

The Wärtsilä 32 engine consists of the following main components:

- Engine block and crankshaft;
- Bearings and connecting rods;
- Cylinder liners and pistons;
- Cylinder heads and camshafts.

Engine block and crankshaft

An engine block is a closed “box” construction that provides a durable body for all engine components mounted to it. It’s made of nodular cast iron and machined in one piece. The engine block is mounted directly on top of a common base frame and it also absorbs internal forces during the engine operation. A charge air receiver as well as cooling water and lubricating oil channels are integrated into the engine block. A wet type oil sump made of welded steel is mounted under the engine block. Crankcase covers, made of light metal, are sealed against the engine block by rubber sealing. [29, 35]

An engine crankshaft is made of high tensile steel and forged in one piece. It’s mounted in the engine block in an under slung way. The crankshaft is fully balanced by counterweights that are fitted on webs of the crankshaft providing a proper oil film for all bearings. [29, 35]

Bearings and connecting rods

Main bearings and big end bearings (crank pin bearings) are fully interchangeable trimetal or bimetal half shell bearings. These bearings have a steel packing and a soft running layer with corrosion resistance. Main bearing caps are made of nodular cast iron, which are fixed from below and sideways providing a rigid crankshaft bearing. [29, 35]

Connecting rods are forged and machined of alloyed steel. They are split horizontally in three pieces allowing removal of a piston and connecting rod parts. Lubricating oil supply for pistons’ cooling, pin bushing and skirt lubrication happens through drillings in the connecting rods. [29, 35]

Cylinder liners and pistons

Cylinder liners are made of cast iron with special alloy elements that provides wear resistance and high strength. The cylinder liner is of a stiff collar design, which is cooled by bore cooling. It’s supported symmetrically at the top of the engine block, and the liner is equipped with an anti-polishing ring at the top to prevent bore polishing. [29, 35]

Pistons consist of an oil cooled steel crown that is bolted to a piston skirt made of nodular cast iron. The piston crown includes two compression rings and one oil scraper ring which all are chrome-plated. The piston skirt and the cylinder liner are lubricated by a pressurized lubricating system with utilizing lubricating nozzles in the piston skirt. [29, 35]

Cylinder heads and camshafts

Cylinder heads are made of nodular cast iron. The cylinder liner is fixed to the cylinder block by hydraulically tightened studs. Each cylinder head has two inlet valves and two exhaust valves, which all are equipped with rotators. Exhaust valve seat rings are water cooled. [29, 35]

Camshafts are made up of one-cylinder pieces with integrated cams. The bearings of the camshafts are located in integrated bores in the engine block casting. The camshafts are driven by the crankshaft through a gear train. [29, 35]

4.2.1.5 Engine mounted equipment and connections

The following main components are mounted on or connected to the engine:

- Flywheel and turning device;
- Turbocharger (TC), charge air waste gate (AWG), exhaust gas waste gate (EWG);
- Speed governor, electric fuel feed pump;
- Other connections (flexible coupling, hoses and bellows).

Flywheel and turning device
A flywheel is fastened to the engine crankshaft with fitted bolts and is located at the driving end of the engine. The generator is connected to the flywheel with a flexible coupling. [29, 35]

The engine is equipped with an electrically driven turning device that enables slow turning of the engine crankshaft. For fine adjustment of the crankshaft position, the turning device has also a hand wheel. The engine start-up is forbidden while the turning device is being used. [29, 35]

Turbocharger (TC), charge air waste gate (AWG), exhaust gas waste gate (EWG)
A turbocharger, a charge air waste gate (AWG) and an exhaust gas waste gate (EWG) are described in Section 4.3 as they are components of the engine auxiliary systems.

Speed governor, electric fuel feed pump
A speed governor of the engine is described in Section 4.4 belonging to the electrical and automation system. An electric fuel feed pump is a component of the engine auxiliary system and is described in Section 4.3.

Other connections
The engine is connected to the generator with flexible coupling and is fastened to a rigid common base frame. The auxiliary systems are connected to the engine by flexible hoses and bellows between external and internal piping. [29, 35]

4.2.2 Generator

The generator that operates with the Wärtsilä 32 EDG engine is a medium voltage (MV) or low voltage (LV) synchronous alternative current (AC) generator with a brushless excitation system. The generator is mounted in horizontal position to the common base frame and is located at the driving end of the engine. Torque from the engine crankshaft is transmitted to the generator shaft via flexible coupling, which is located between the engine flywheel and the generator shaft. The function of the generator is to convert mechanical power of the engine into electricity. The engine rotates the generator's rotor inside stator to generate a magnetic field inside the synchronous generator. Rotor windings of the generator are provided by direct current (DC) for producing the magnetic field in the rotor (excitation based on Ampere's law). A three-phase medium voltage (MV) is induced in stator windings generated by rotating magnetic field (induction based on Faraday's law). [29, 35, 36]

4.2.2.1 Main characteristics of EDG generator

The generator of the EDG is designed for continuous operation (duty type S1) together with the engine. Typically the generator is dimensioned such that temperature rise in stator and rotor windings is not exceeding class B limits (approx. 85 to 95 °C) when the generator is operating at rated power. The insulation class of the generator is at least class F (approx. 110 to 115 °C). The enclosure rate of the generator can be either class IP44 or IP23. The rated power factor (PF) of the generator (relation between active and apparent power) is typically 0.8. The generator's efficiency is approximately 96 % when operating at nominal load with power factor 0.8. Rotational speed of the generator is fixed to electricity grid's frequency by designing the generator construction with 8 or 10 poles. The generator with 8-pole rotor rotates at 750 rpm to generate electricity at 50 Hz and 10-pole generator rotor rotates at 720 rpm to generate 60 Hz electricity. Table 6 below summarizes the main characteristics of the synchronous generator operated with Wärtsilä 32 EDG engine. [29, 35, 36, 37, 38, 39]

Table 6: Main characteristics of generator operated with Wärtsilä 32 EDG engine. [29, 35, 36, 37, 38, 39]

Typical generator operated with Wärtsilä 32 EDG engine	
Duty type	Continuous operation (S1)
Temperature rise class in stator and rotor windings	Class B (approx. 85 – 90 °C)
Insulation class	Class F (approx. 110 – 115 °C)
Enclosure rate	IP44 or IP23
Rated power factor	0.8 (typical value)
Electrical efficiency	96 %
Electricity frequency	50 Hz or 60 Hz (depending on grid characteristics)
Construction	8- or 10-pole (depending on grid frequency)

4.2.2.2 Main components and systems

The generator consists of the following main components and systems:

- Rotor and shaft;
- Stator core and frame;
- Terminal enclosures (voltage and current measurement transformers);
- Excitation system;
- Bearing and lubrication system;
- Cooling system.

Rotor and shaft

The generator's rotor is of a salient pole type construction where magnetic poles are protruding out from surface of the rotor. A rotor's shaft is forged of steel and salient poles are manufactured of steel sheets pressed together by means of bars and end plates. A damper winding on rotor poles stabilizes the rotor during load changes, which makes the generator suitable for parallel operation with the grid. To be precise, the damper winding minimizes effects of power swings and prevents asynchronous (or out-of-phase) operation in parallel operation. The rotor construction includes also fans and parts of an exciter rotor, which are fitted on the shaft. [29, 35, 36]

Stator core and frame

The stator is a stationary part of the generator. A stator frame is a rigid steel structure resting on a machined feet. A stator core is built of thin electric steel sheet laminations that are insulated from heat and wear with an inorganic resin. The cooling of the stator is carried out by means of ventilation ducts, which go through the stator core evenly and radially. Stator windings are form-wound, copper made and insulated with vacuum pressure impregnated epoxy-mica insulation. The stator windings are also fastened with a strong bracing to withstand possible electro-mechanical shocks. Space between the stator windings and core is tight providing sufficient thermal conductivity. [29, 35, 36]

Terminal enclosures (voltage and current measurement transformers)

All winding ends of the stator are brought to terminal boxes, which are located on sides or on top of the generator. Monitoring terminals and auxiliary equipment of the generator typically have separate terminal boxes. However, terminal enclosures may also contain current and voltage measurement transformers based of the generator supplier's design. [29, 35, 36]

Excitation system

The excitation method is based on a brushless excitation that is suitable for self-excitation of the generator. The excitation system is also a part of instrumentation and control system (I&C-system), and its operating principle is described Section 4.4.1.4. An excitation circuit consists of an automatic voltage regulator (AVR), a brushless exciter, a pilot exciter (permanent magnet generator, PMG) and a rotating rectifier with diode bridge arrangement. The AVR module and its back-up module are located in local control panel (LCP) of the EDG set. The brushless exciter and the rotating rectifier are mounted on the rotor shaft. The pilot exciter (PMG) is located at non-drive end of the generator and it's mounted directly to the shaft. Figure 10 below shows a principle drawing of the generator with the PMG excitation system. [29, 35, 36]

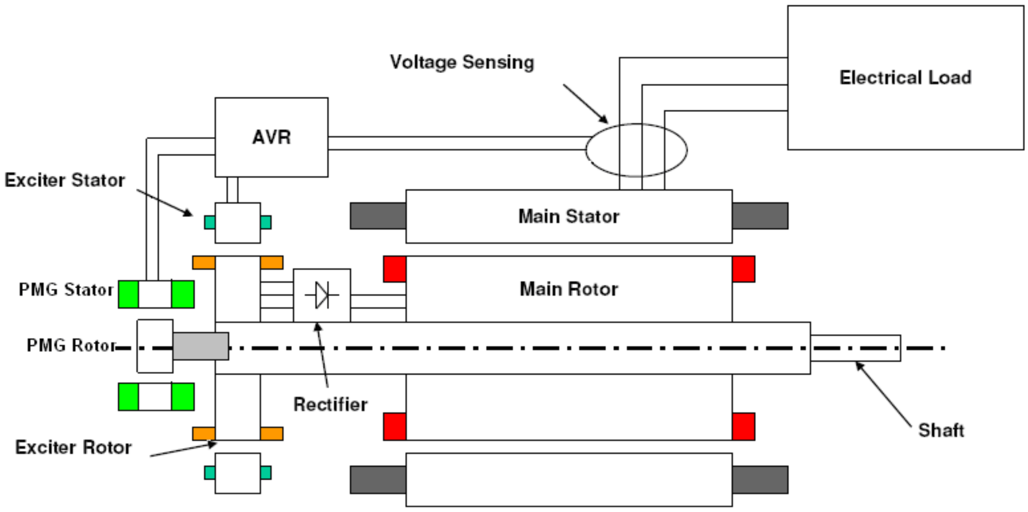

Figure 10: Principle drawing of generator with PMG excitation system. [40]

The generator's excitation system is completely independent of any external power sources by using the permanent magnet generator (PMG) as a pilot exciter. The PMG produce excitation power that is regulated by the AVR and fed to the brushless exciter field windings. Then induced armature current (three-phase AC) is converted to DC by the rotating rectifier and fed into the main rotor windings through the rotating rectifier diode bridge. [29, 35, 36, 40]

Bearing and lubrication system

Typically the generator is equipped with two axial sleeve bearings which are mounted on both ends of the generator shaft. Smaller size generator (i.e. for 6L32 engine) can be equipped with roller bearings. In the sleeve bearing solution, the lubrication system of the generator bearings is a self-contained closed system, thus it's not connected to the engine lubrication oil circuit. However, flood lubrication might be required for large generators (i.e. for 16V32 and 20V32 engines) to ensure sufficient lubrication and cooling. In some cases smaller EDG generators may have to equipped with bearing oil cooling systems or connected to the lubricating oil system of the engine due to a combination of relatively heavy rotor (over-dimensioned generator) and potentially high ambient temperature. [35, 41, 42]

Cooling system

The generator is air-cooled and open ventilated. Cooling air is taken from the engine room by means of a shaft-mounted fan equipped with filters. Waterproofness of the generator is realized by protecting air inlets and outlets with louvers and filters. In normal situation, the generator is in stand-by mode (as well as the engine) and therefore some condensation water may arise in the generator casing especially in cold ambient conditions. To prevent water condensation during stand-by operation, the generator is equipped with an anti-condensation heater. After a start-up, the anti-condensation heater is switched off. The generator includes also temperature sensors, whose function is to indicate temperature variations in bearings and windings. [29, 35, 36, 42]

Flexible coupling
The flexible coupling connects shafts of the engine and the generator together. The flexible coupling is located between the engine flywheel and the generator shaft, and it minimizes torsional vibration as well as provides torque damping for the whole shaft system. Since the coupling is flexible, a slight misalignment between shafts is allowed, and the engine crankshaft is not loaded by any external bending forces. In addition, possible engine firing irregularities are prevented from being transmitted to the generator. The flexible coupling elements are made of rubber or elastic steel spring packs. [29, 35, 43]

4.2.3 Common base frame

The engine and the generator are rigidly fastened to the common base frame. It is a welded steel structure, whose function is to provide a stable structural support and a torsion resistant platform for the engine and the generator. In addition, the common base frame provides a support for piping that connects the engine and its auxiliary systems' parts outside the engine. Also some of the EDG set's components are mounted on the common base frame such as an electrically driven fuel oil feed pump and a fuel oil fine filter. The common base frame of the EDG set is always designed project specifically wherein all design aspects such as varying engine cylinder configurations, generator dimensions and weight, and a seismic analysis are taken into account. [29, 35, 43]

4.2.3.1 Main components

The common base frame is equipped with the following main components and systems:

- Flexible mounting (steel spring packages);
- Damping (viscose dampers) and fixing components (undercut anchors);
- Steel chocks.

Flexible mounting
The common base frame is flexibly mounted to a concrete foundation. The flexible mounting is achieved by steel spring packages, which are fastened on the bottom of the common base frame during an installation on-site. Typically the steel spring packages are attached directly to the concrete foundation. The purpose of the flexible mounting is to reduce transmissions of dynamic forces and vibrations between the common base frame and the concrete foundation. The flexible mounting enables that the common base frame is isolated from the concrete foundation and therefore is not affected by the difference in thermal expansion coefficient between the foundation and base frame. Addi-

tionally structure borne noise level is greatly reduced with the flexible mounting solution. [29, 35]

Damping and fixing components

To maintain operability of the EDG set during and after seismic events (i.e. earthquake), the common base frame set may require damping. Necessity of damping is determined by a preliminary seismic analysis that is made based on floor spectra received from the customer. The damping itself is achieved by using viscose dampers, which are mounted next to the common base frame similar way as steel spring packages. They are fastened either directly to the concrete foundation or with special steel bar arrangement located under the viscose dampers. Together with the steel spring packages, the viscose dampers stabilize the EDG set effectively and limit amplitudes when the EDG set encounters the resonance that occurs at during start-up, shutdown, load appliance, seismic event or their combinations. The steel spring packages and the viscose dampers are fixed to the concrete foundation with undercut anchors, bolts and nuts. The undercut anchoring transfer tension loads to the concrete foundation. Both damping and flexible mounting arrangements can be seen in Figure 11 below. [29, 35, 43]

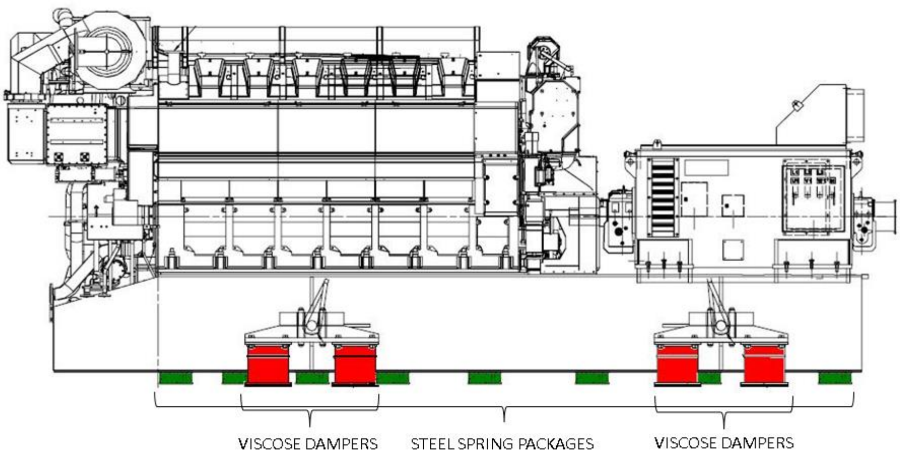

Figure 11: Flexible mounting and damping of EDG set. Steel spring packages (green) and viscose dampers (red) are mounted next to common base frame. [43]

Steel chocks

Steel chocks can be used to align the generator properly on the common base frame. Typically, steel chocks are re-adjustable mounting chocks that can be used for all types of rotating or critically aligned machinery (for example the EDG assembly). These chocks can be used instead of rigid steel chocks, shims or epoxy resin chocks. Re-adjustable chocks provide possibility of aligning and re-adjusting at every re-alignment event, and they also absorb vibrations similarly like a vibration damper. These re-adjustable steels chocks include a spherical top plate and mating middle section allowing self-leveling configuration that enables angular differences up to 4°. [44]

Foundation
The foundation is a concrete block that is casted in a single continuous pour. The concrete foundation is separated from a surrounding floor slab with an elastic joint, and a drain channel connected to an oily waste sump runs around edges of the foundation. The foundation is dimensioned specifically to give proper support for the EDG set, and it may be reinforced if necessary. [29, 35, 43]

4.3 Auxiliary systems

The auxiliary systems of the EDG set are described so that each auxiliary system is divided into an internal and an external system. The internal auxiliary system consists of components, which are located inside the engine or are mounted directly on the generating set. The external auxiliary system comprises equipment that is located outside the EDG set. Proper function of the EDG depends directly on the auxiliary systems. Figure 12 below shows schematic overview of flow circuits and connections of the auxiliary systems, which are as follows:

- Fuel oil system (red);
- Lubricating oil system (yellow);
- Cooling water system (blue);
- Charge air and exhaust gas systems (black);
- Compressed air systems (green);
    - Starting air system;
    - Instrument air system.

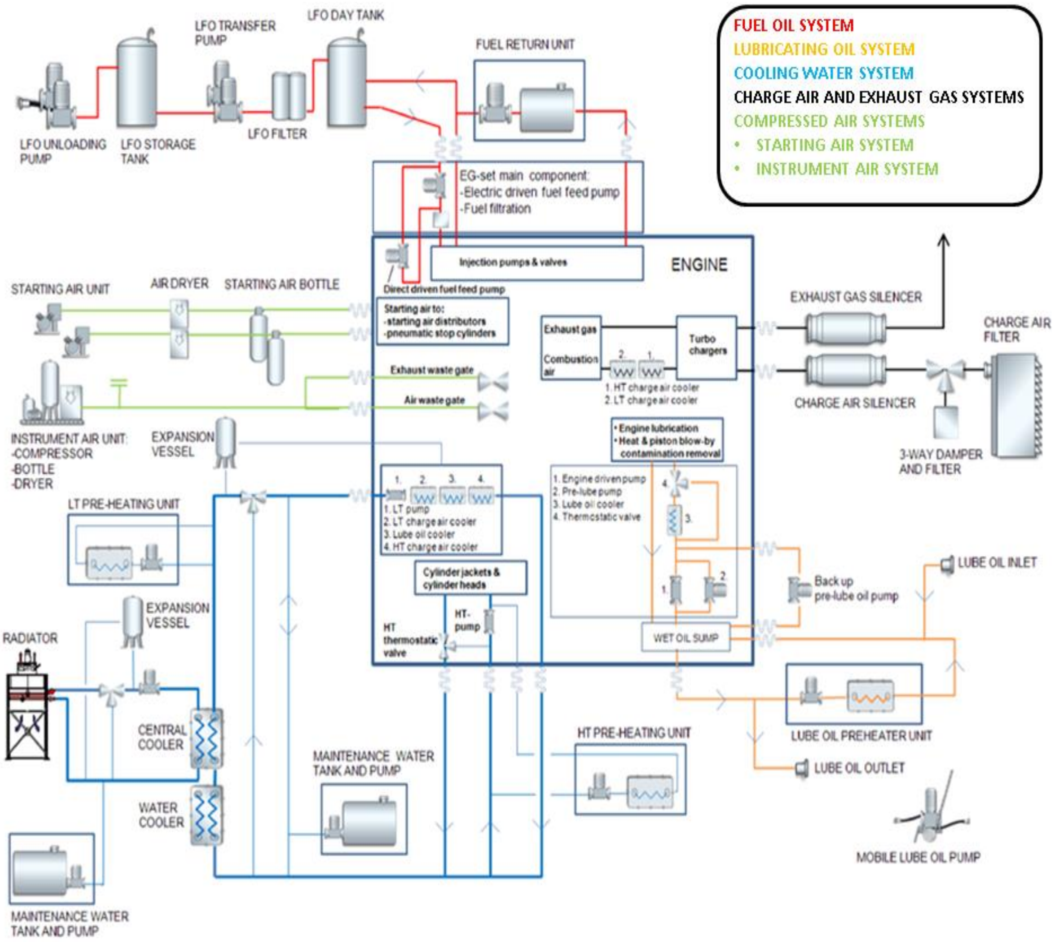

Figure 12: Schematic overview of EDG auxiliary systems. [2, 43]

4.3.1 Fuel oil system

The function of the fuel oil system is to supply fuel oil to the engine with regard to following parameters in correct state:

- Viscosity [cSt] (depends on temperature [°C]);
- Filtration grade [Fm];
- Flow over the engine [m^3/h];
- Pressure [bar].

As mentioned earlier, the Wärtsilä 32 EDG engine consumes only high quality light fuel oil (LFO). Characteristics of LFO are discussed later in Section 6.3.1.

The fuel oil system can be divided such that it consists of storage and transfer system, feeding system, and collection and unloading systems. The fuel oil storage and transfer system is used for storing LFO in a fuel oil storage tank and a fuel oil day tank. The system also transfers LFO from the storage tank to the day tank. The fuel oil feeding and collection system supplies LFO from the day tank to the engine, and collects the engine leak fuel oil and circulates it back to the day tank. The function of the unloading system is to receive LFO from a transportation vessel and pump it to the fuel oil storage tank. [29, 35]

4.3.1.1 External fuel oil system

The external fuel oil system of the EDG set consists of the following main components, which can be seen in Figure 13 below:

- Storage tank;
- Piping;
- Transfer pumps;
- Fuel oil filter;
- Day tank;
- Return fuel oil unit;
- Fuel oil cooler.

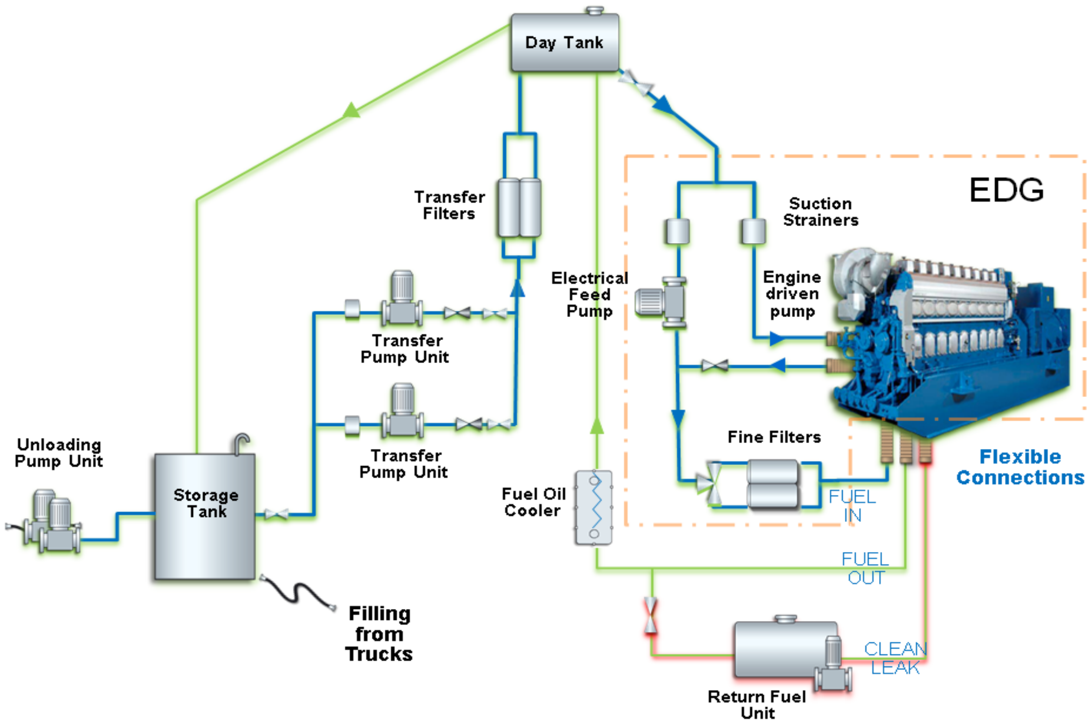

Figure 13: Schematic flow diagram of external fuel oil system of EDG set. [45]

Storage tank

LFO is stored in the fuel oil storage tank, which can be located outside or inside the EDG building. Typically, each EDG is served by one storage tank that provides a long-term storage for LFO and ensures that transfer pumps are under static pressure. The storage tank is equipped with fuel oil level switches for monitoring LFO surface level in the tank. In addition, the storage tank includes local indicators that measure temperature of LFO and surface level in the tank as well. In order to ensure pumpability of LFO (pour point shall not be exceeded), it must be stored in correct temperature in the tank. Typically the storage tank doesn’t demand any insulation due to sufficient volume of LFO in the tank. However, if ambient conditions are extremely cold at site, insulation may be required. Normally the storage tank is placed on a ground level, but it’s possible to install the tank in the EDG building’s basement level as well. [29, 35, 46]

Piping

The fuel oil pipeline between the storage tank and the day tank is located outside the EDG building. In case ambient conditions are extremely cold at site, the fuel oil piping may be equipped with electrical trace heating arrangement to avoid freezing and to ensure fluent flow of LFO inside the piping. [45]

Transfer pumps

LFO is transferred from the storage tank to the day tank along the piping by means of two redundant fuel oil transfer pumps. These transfer pumps ensure that LFO surface level in the day tank is sufficient at all times. Typically, the transfer pumps are located in vicinity of the storage tanks. Normally, one transfer pump (primary) is operating while other transfer pump (secondary) is in stand-by and works as a back-up. The primary transfer pump starts and stops automatically depending on LFO surface level in the day tank. Both transfer pumps are of a screw type, and are furnished with pressure relief valves and suction strainers. [29, 35, 46]

Fuel oil filter

Before LFO enters to the day tank, it’s filtered by a fuel oil filter located at an inlet pipe to the day tank. The filter is of a duplex type where two switchable filter housings are connected in parallel. The fuel oil filter collects impurities from LFO to interchangeable paper inserts. It’s also equipped with a pressure difference switch that indicates local pressure and sends an alarm signal to the EDG’s control system if pressure difference reaches a predefined high set value. [29, 35, 46]

Day tank

The fuel oil day tank is located inside the EDG building. The day tank works as an intermediary storage for LFO before it enters the engine. The day tank includes also functions such as collecting LFO back from the engine and from a return fuel oil unit, and de-aerating fuel oil piping as well as providing static pressure for fuel oil feed pumps. Positive static pressure is achieved by placing the day tank on a higher elevation in relation to the fuel oil feed pumps. The day tank is furnished with fuel oil level switches, which monitor surface level, give signals to the transfer pumps to start and stop when required, and initiate an alarm to the control system in case surface level in the day tank is too low. Additionally, the day tank has an overflow connection from which LFO is gravitationally led back to the storage tank to prevent overfilling or spillage of the day tank. From the day tank, LFO flows by means of gravitation towards the EDG. An inlet pipeline connection before the EDG may be equipped with a quick closing valve that can be used to cut LFO supply to the engine in case a risk of fire inside the EDG building or fuel oil leakage from the pipeline. [29, 35, 46]

Return fuel oil unit

When the engine is operating at its nominal power, approximately 20 to 25 % of LFO is consumed in the combustion process. The pressure relief valve maintains LFO pressure on the engine at pre-defined level. Excess LFO is led directly from the engine to the day tank through cooling. However, typically small amount of LFO that enters to the engine is leaking out from the system. This clean leak fuel oil can be re-used and therefore the system is equipped with a return fuel oil unit. Dirty leak fuel oil with possible contaminants can’t be re-used, thus it’s drained out from the engine to a drainage tank. Clean leak LFO typically originates from fuel oil injection pumps whereas dirty leak LFO originates mainly from leakages that occur during maintenance. [35, 46]

The fuel oil return unit collects clean leak LFO from the engine and returns it back to the day tank. The unit consists of a return fuel oil container and a return fuel oil pump. The pump is of a screw type driven by an electric motor, and the container is equipped with surface level switches that give signals to the electric motor to start and stop. The surface level switches also indicate an alarm signal to the control system if clean leak LFO surface level inside the container is too high. [35, 46]

Fuel oil cooler

The temperature of LFO always rises when it flows through the engine circulation. This warming may cause fuel oil injection problems at high ambient temperatures because of low viscosity of LFO. To prevent this problem, the fuel oil system is equipped with a fuel oil cooler. The fuel oil cooler is located at the fuel oil return pipeline between the engine and the day tank. This cooler is of a plate heat exchanger type, wherein cooling is provided from the LT-cooling water circuit. Alternatively, LFO cooling can be arranged by water cooled radiators or chillers. [45, 46]

4.3.1.2 Internal fuel oil system

The internal fuel oil system of the EDG set consists of the following main components, which also are shown in Figure 14 below:

- Fuel oil feed pumps with suction strainers;
- Fuel oil fine filter;
- Fuel oil injection pumps.

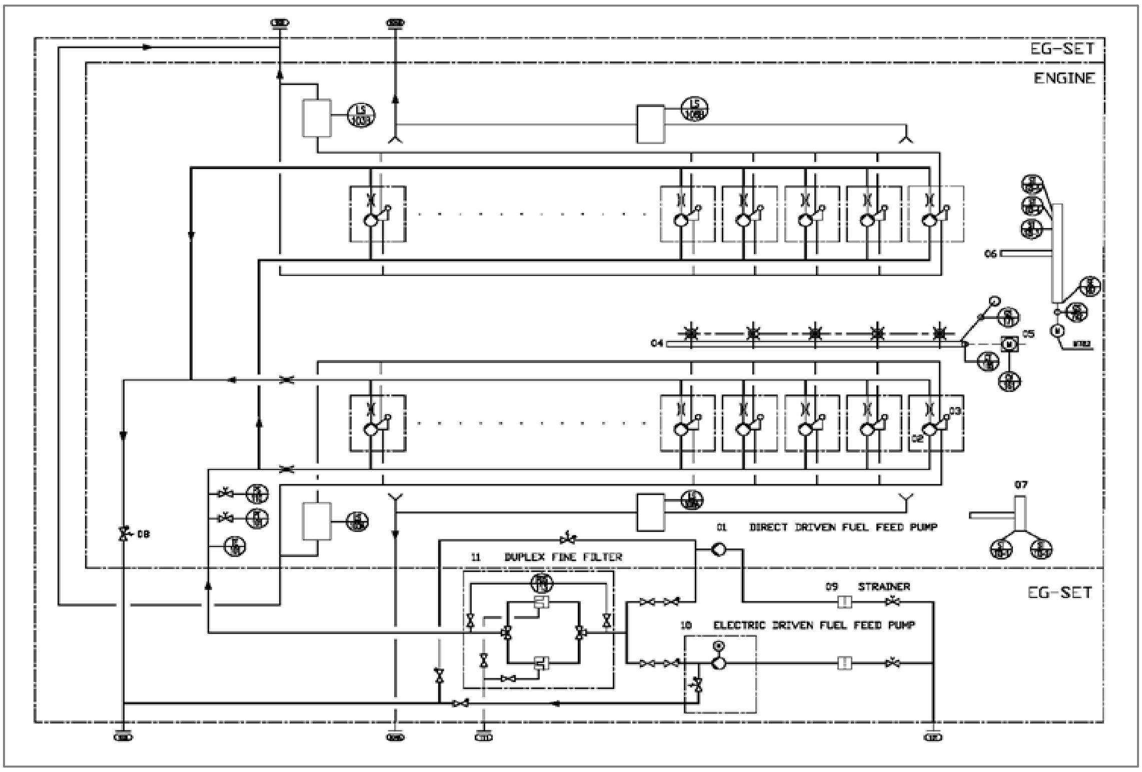

Figure 14: Flow diagram of typical internal fuel oil system of EDG set. [45]

Fuel oil feed pumps with suction strainers

From the day tank, LFO flows to the engine through suction strainers that protect fuel oil feed pumps by removing solid particles from LFO. The EDG set is equipped with two fuel oil feed pumps, an engine driven and an electrical driven. The engine driven fuel oil feed pump is a primary pump that circulates LFO over the engine. When the engine is operating at its nominal power, LFO flow rate over the engine is 4 to 5 times greater than LFO consumption in the engine. The engine driven pump is of a screw type coupled to the crankshaft by gear wheels. It’s equipped with a pressure relief valve that protects the fuel oil system from overpressure by returning LFO from pressure side to suction side of the pump in the case when a predefined high set value is reached. [35, 46]

The electrical driven fuel oil feed pump is installed in parallel with the engine driven pump. It’s a screw type pump driven by an electrical motor. Primarily this electrical driven feed pump is used for de-aerating the fuel oil system after maintenance. It can also be used as a back-up for the engine driven pump if the engine driven fuel oil feed pump cannot maintain LFO pressure over the engine at sufficient level for some reason. The electrical driven pump starts automatically in case LFO pressure at inlet of the engine drops below a pre-defined low set value. [35, 46]

Fuel oil fine filter

Before LFO is injected in the cylinders, a fuel oil fine filter purifies LFO. The fine filter is located downstream from the fuel oil feed pumps. The fine filter is of a duplex type and operates as same principle as the fuel oil filter outside the engine does. After LFO has passed the fine filter, temperature and pressure of LFO is measured by a temperature sensor and a pressure transmitter. [35, 46]

Fuel oil injection pumps

After filtering, LFO is supplied to fuel oil injection pumps, which press LFO through injection pipes to injection valves and nozzles, from where LFO is injected in the cylinders in correct timing. Each cylinder is equipped with one fuel oil injection pump. The injection pumps are of a cylinder type equipped with separate roller tappet and they are lubricated by lubricating oil (LO). In addition, the injection pumps include pneumatic stop cylinders, which in case of emergency can cut LFO supply leading to the engine shutdown. The injection pumps are mounted in a multihousing structure. All high pressure fuel oil pipes in the injection system are double walled and equipped with alarms in case of excess leakage or piping break. [29, 35, 46]

4.3.2 Lubricating oil system

The function of the lubricating oil system is to provide lubricating oil (LO) in right quality, temperature and pressure for all main moving parts of the engine such as bearings and cylinder liners. In addition, the lubricating oil system enables crankcase ventilation and has a cooling function, because the system cools piston tops and turbocharger bearings. [29, 35]

The lubricating oil system can be divided into cleaning, cooling, pressure control and refilling systems. The cleaning system maintains cleanliness of LO before it enters the engine. The cooling system cools and regulates LO flow over the engine. The pressure control system ensures that the engine is provided with right quantity of LO at correct pressure. This system includes pre-lubrication and ordinary lubrication functions of the engine. The refilling system is used for draining and refilling the lubricating oil system to cover LO consumption of the engine. [29, 35]

4.3.2.1 External lubricating oil system

The external lubricating oil system of the EDG set consists of the following main components, which are shown in Figure 15 below:

- Lubricating oil transfer pump;
- Oil mist coalescer;
- Lubricating oil service tank/make-up tank (optional).

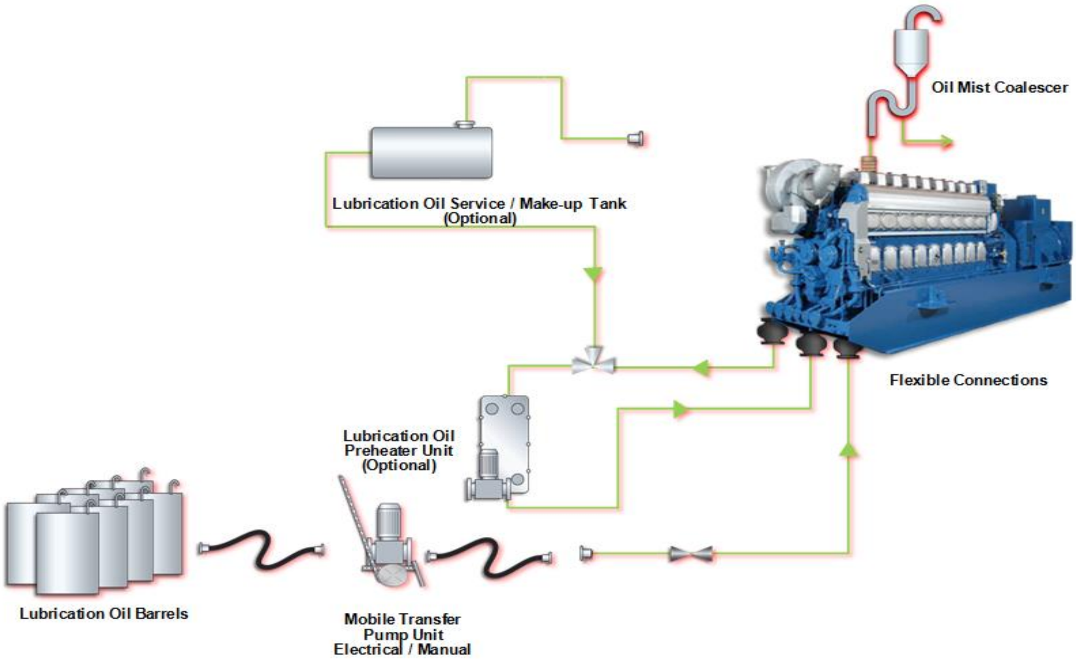

Figure 15: Schematic flow diagram of external lubricating oil system of EDG set. [47]

Lubricating oil transfer pump

A lubricating oil transfer pump is used for filling, refilling and emptying the engine oil sump. The LO transfer pump is connected to the inlet connection, if LO is delivered to the oil sump for filling or refilling. The transfer pump is connected to the oil sump outlet connection during emptying, which is done when the EDG set is under maintenance. The type of this mobile LO transfer pump unit can either electrical or manual type. It's equipped with flexible hoses that are connected to the engine inlet or outlet depending on the function. [35, 48]

Oil mist coalescer

The engine is equipped with a ventilation pipe with flexible connection from the crankcase. Gases inside the crankcase are led out in order to prevent that blow-by gas won't build up pressure inside the crankcase and the oil sump. Blow-by gas originates mainly from the turbocharger and is formed by reciprocating movement of the pistons in the cylinders. The gases contain small traces of LO, and this mixture is called oil mist. The ventilation pipe is connected to the oil mist coalescer that reduces oil traces from the gases before they are released to atmosphere. The oil mist condensate is drained back to the oil sump. [35, 48]

Lubricating oil service/make-up tank (optional)

Instead of pumping used LO from the engine into oil barrels, a lubricating oil service/make-up tank with enough volume can be installed in the tank yard. There are three different types of tanks for storing LO from the engine. Fresh LO can be stored in the make-up tank for mixing LO changes and compensating LO consumption of the engine.

The oil sump or EDG’s associated LO tank is replenished by LO pumps or by means of gravity. The LO make-up tank is filled through a pipe feed from the mobile LO transfer pump unit. The LO service tank and the used LO tank represent slightly different purposes. The LO service tank is used as a temporary storage, if the engine and its oil sump has to be emptied on LO in case the EDG is under service or maintenance. After service work, LO is pumped back to the engine and oil sump. The used LO tank is used as a storage place for used LO that normally can’t be utilized due to poor quality. [47]

4.3.2.2 Internal lubricating oil system

The internal lubricating oil system of the EDG set consists of the following main components, which can be seen in Figure 16 below:

- Lubricating oil sump;
- Main lubricating oil pump;
- Pre-lubricating oil pump;
- Lubricating oil cooler (LOC);
- Thermostatic valves;
- Automatic filter;
- Centrifugal filter;
- Lubricating oil pre-heater (optional).

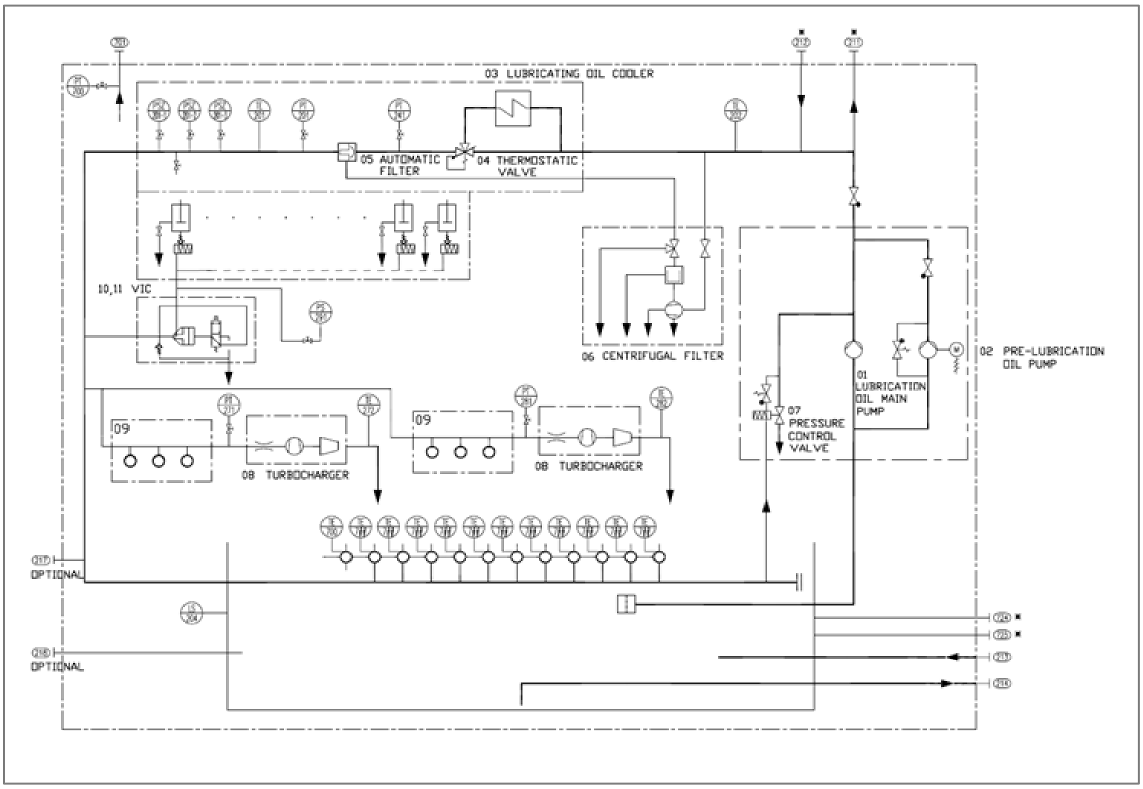

Figure 16: Flow diagram of typical internal lubricating oil system of EDG set. [47]

Lubricating oil sump

The engine is equipped a wet type lubricating oil sump mounted under the engine block. The function of the oil sump is to store enough LO for the engine consumption at all operating modes for several days. The oil sump also collects LO from the engine lubricating circuits. The oil sump capacity depends on the size of the engine. The surface level of LO in the oil sump is monitored by a level switch that indicates an alarm in case of low LO surface level. An oil dip stick can be used to measure oil volume in the sump as well. [35, 48]

Main lubricating oil pump

The engine driven main lubricating oil pump sucks LO from the oil sump, pressurizes the lubricating oil system and circulates LO over the engine. The main lubricating oil pump can be of a screw or gear type and it’s driven by a pump gear coupled to the engine crankshaft. A pressure regulating valve is installed on the housing of the pump. This valve protects the lubricating oil system from overpressure by returning LO back to the oil sump. The engine driven pump is located at free end of the engine, and is installed in horizontal position. [35, 43, 48]

Pre-lubricating oil pump

The electrically driven pre-lubricating oil pump is installed in parallel with the engine driven main lubricating oil pump. The function of the pump is to fill the lubricating oil system of the engine and also generate some pressure in the lubricating oil system before the engine start-up. The pump operates continuously in order to keep the engine pre-lubricated in stand-by mode. The pump is of a gear type and it is driven by an electric motor. The pump includes also an adjustable pressure control valve. The pump is located at the free end of the engine and it is installed in vertical position. [35, 43, 48]

Lubricating oil cooler (LOC)

As for LFO temperature rise during circulation over the engine, also LO temperature increases when circulating inside the engine during operation. When the engine is operating at full load, LO temperature raises up to 75-80 °C. The allowable temperature of LO at the engine inlet is about 63 °C. Therefore LO must be cooled before entering the engine. This is done inside a lubrication oil module that is mounted on the engine. The LO module consists of a lubricating oil cooler (LOC), automatic back-flushing fine filter with safety filter, centrifugal filter and three-way thermostatic valves. The LOC cools down LO to the required temperature level. The cooler is of a tube stack type, wherein LO flows outside tubes while LT-water flows inside these tubes through the cooler. [35, 43, 48]

Thermostatic valves

After cooling, LO is led to thermo-mechanical three-way thermostatic valves, which control the inlet temperature of LO. The valves are of a wax element type and the set point temperature of each valve is 63 °C. There are five valve units installed on the lubricating oil module. These valves are also equipped with a manual override function to enable manual use in abnormal operating conditions. [35, 43, 48]

Automatic filter

From the three-way thermostatic valves, LO flows for filtration before entering the engine. The filtration is executed by an automatic filter and a centrifugal filter. The lubricating oil automatic fine filter removes particles from LO. The automatic filter is a full flow filter so that whole LO flow passes through the filter. The driving force for the filter is given by the oil flow through a turbine. The filter allows continuous operation without manual cleaning or maintenance, and clogging of the filter is monitored by a local indicator. [29, 35, 43, 48]

Centrifugal filter

Contaminated LO from the automatic filter is led to the centrifugal filter where LO is subjected to a high centrifugal force. The oil dirt is deposited on walls of the centrifugal filter rotor in the form of heavy sludge. The centrifugal filter removes constantly impurities such as particles and water from LO. Cleaned LO from the filter is returned back to the oil sump. Temperature and pressure of LO is measured and monitored by specific switches and sensors. The pressure monitoring is based on 2-out-of-3 principle as it is initiating an engine trip in all operating conditions, whenever pressure of LO reaches the predefined low limit value. [29, 35, 43, 48]

Lubricating oil pre-heater (optional)

The lubricating oil system can be equipped with a pre-heater. The minimum recommended LO temperature is 40 °C in the internal system. If there is a risk that LO temperature may fall below this value due to cold ambient conditions, the lubricating oil pre-heater unit can be considered. LO is pre-heated during stand-by to avoid too low viscosity for the LO pumps, which ensures safe starting of the engine. The lubricating oil pre-heating can be arranged by two different ways: with an electric preheating unit (pre-heater and pump) or with a heat exchanger unit (heat exchanger and pump) where pre-heated HT-water heats up LO. [47]

4.3.3 Cooling water system

The function of the cooling water system is to remove heat from the engine components such as cylinder jackets and cylinder heads. The cooling water system also cools fuel oil, lubricating oil and charge air systems as well as maintains the engine in pre-heated condition during stand-by mode. Excess heat is removed from the main heat sources of the engine, which are as follows: [29, 35, 43]

- Engine jacket (general term used for combination of cylinder jackets, cylinder heads, and turbocharger cooling);
- HT-charge air cooler (HT-CAC);
- LT-charge air cooler (LT-CAC);
- Lubricating oil cooler (LOC);
- Fuel oil cooler.

The cooling water system of the EDG set can be divided into two primary circuits; low-temperature water circuit (LT-circuit) and high-temperature water circuit (HT- or jacket circuit). The cooling water system that is described below is based on one-circuit (1-C) configuration, which is typically preferred for the EDG. The cooling water system outside the EDG set can be arranged in different configurations (2-C or combined solution) depending on ambient conditions and on the customer's requirements, but these are not studied further. [29, 35, 49]

4.3.3.1 External cooling water system (1-C)

The external cooling water system of the EDG set consists of the following main components, which can be seen in Figure 17 below:

- HT-preheating unit (jacket water pre-heater);
- Radiators/Raw water cooler (or combination);
- LT-thermostatic valve;
- LT-preheating unit (for cold conditions only);
- Expansion vessel;
- Maintenance water tank;
- Fuel oil cooler.

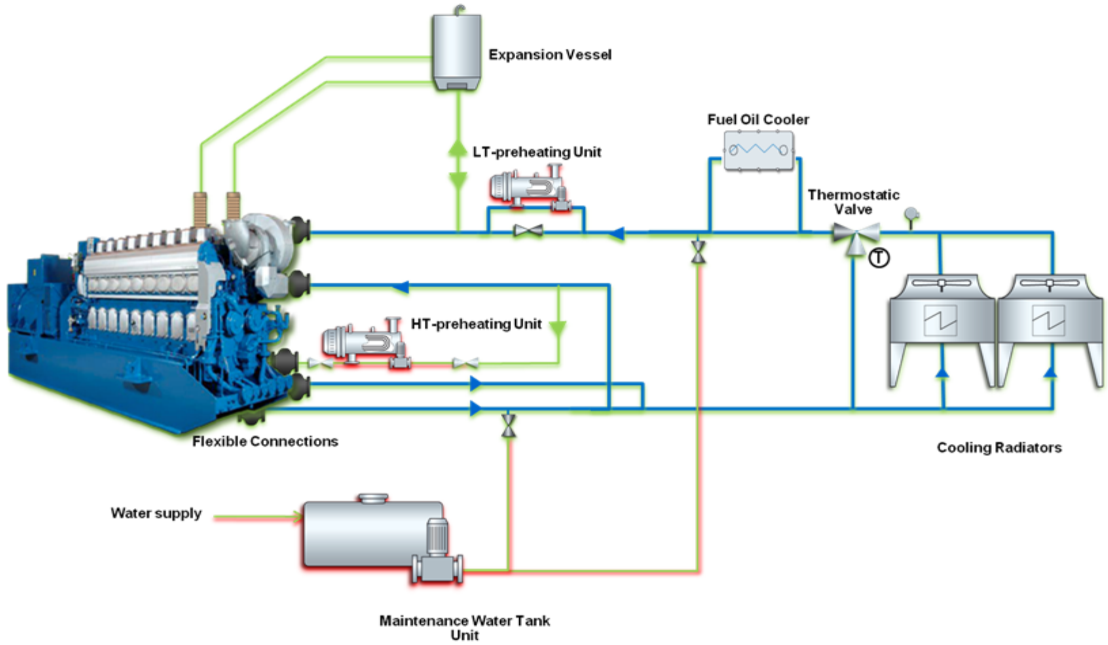

Figure 17: Schematic flow diagram of external cooling water system with radiator cooling (1-C configuration). [50]

Functions of external HT- and LT-circuits

The main function of the HT-water circuit is to transfer heat generated by the engine jacket for dissipation. The secondary function of the HT-circuit is to maintain the engine jacket pre-heated to facilitate start-up. The function of the LT-circuit is to transfer heat generated from charge air coolers (CACs) and from the lubricating oil cooler (LOC) to an external cooling media, which can be either ambient air or external cooling water source. The LT-circuit also maintains temperature of LT-water at beneficial level for the engine cooling process. Secondary functions of the LT-circuit are as follows: [29, 35, 51]

- Enable filling of cooling water system with water;
- Provide water storage for cooling water replenishment and additive mixing;
- Provide static pressure for cooling water pumps;
- Maintain LT-water pre-heated in cold ambient conditions;
- De-aerate cooling water system.

HT-preheating unit

The external HT-circuit is equipped with a pre-heating unit that is connected in parallel with an engine driven cooling water pump. The HT-pre-heating unit pre-heats HT-water at least up to the set point temperature of 70 °C before it enters the engine jacket. Pre-heating is only performed during stand-by to ensure that the engine is ready for start-up. When the engine jacket is pre-heated, temperature gradients during engine start-up are minimized, clearances of engine components are optimized and adequate lubricating oil properties are achieved. The HT-pre-heating unit consists of an electrically driven centrifugal pump and an electric heater with built-in temperature switches. [29, 35, 51]

Cooling radiators

The function of cooling radiators is to remove heat from the engine HT-circuit for dissipation. Typical radiator type used is of a horizontal, single-circuit type. The radiator body typically consists of copper tubes equipped with aluminum or copper fins. Copper fins may be considered for nuclear applications in acid/salty conditions. The radiator headers made of copper are equipped with drain valves and manual venting valves. Inside the radiator, heat from HT-water is dissipated when it circulates through a finned tube coil that is cooled by a forced air flow. This forced air flow is produced by fans that are driven by an electrical fan motor. The fan motor includes a space heater to prevent water condensation inside the casing of the motor. The heat transfer area inside the radiator may need to be increased if amount of glycol is large in cooling water circuits. Typically radiators are located outdoors where they are installed on the roof of the EDG building in horizontal position. In special cases, the radiators can be placed in a specific radiator room inside the EDG building. Number and size of the radiators per EDG set depends directly on ambient conditions and required capacity of heat transfer from the engine. [29, 35, 51]

Raw water cooler

Raw water coolers can be used when raw water of suitable quality from sea, river, lake or from other cooling water source is available. The raw water cooler is a plate type heat-exchanger, which can be placed outdoors or inside the EDG building. The heat from cooling water is dissipated when it flows through the primary side of the exchanger while the raw water is circulating in the secondary side of the heat exchanger. The raw water should be properly cleaned and filtered before entering the cooler. [29, 35, 51]

Fuel oil cooler

Typically in the EDG applications where LFO is used, the fuel oil requires cooling. The fuel oil cooler is connected to the external LT-circuit right after the radiators or the raw water cooler. The fuel oil cooler is described in Section 4.3.1.1. [50]

LT-thermostatic valve

Temperature of LT-water is maintained at fixed set point value by a LT-thermostatic valve. The valve is of a wax element type, internally sensing and self-actuating three-way valve. It’s functioning in a mixing mode meaning that it divides cooling water from the engine and directs it either to the radiators or the raw water cooler or to by-pass. The LT-thermostatic valve regulates water flow with aid of wax elements that expand as a function of water temperature. The valve is provided with a pre-defined temperature set point, which is not configurable. For the LT-circuit the set point temperature is typically

38 °C. In case LT-water temperature is increasing above the set point value after the valve, it regulates automatically more flow towards the radiators or the raw water cooler. If water temperature after the valve is decreasing, it will direct more water to by-pass and mixing. The valve also has a manual override function to enable manual actuation in abnormal operating conditions. [35, 50, 51]

LT-preheating unit

The LT-circuit may be equipped with a pre-heating unit if there is possibility that minimum ambient temperature can be remarkably low. The function of the LT-pre-heating unit is to maintain the LT-circuit in pre-heated temperature and to maintain heat balance of the engine during no-load (idling) and low-load operation. The LT-preheating unit is located before the engine inlet. The unit comprises an electrically driven centrifugal pump and an electrical heater controlled by a thermostatic switch. Pre-heating of LT-water is initiated automatically in cold ambient conditions whenever LT-water temperature reaches set point temperature of the pre-heating. The set point value is fixed so that charge air temperature in a charge air receiver will not fall below 20 °C in any conditions. [50, 51]

Expansion vessel/tank

An expansion vessel (or tank) is used to provide static pressure for cooling water pumps and to de-aerate the cooling water system. The vessel is equipped with a local surface level indicator and a level switch that sends an indication to the control system in case water level in the vessel reaches its low level set point value. [51]

Maintenance water tank

A maintenance water tank is used for collecting and storing cooling water from the system when the engine is drained for maintenance. The tank enables adding clean water and additives such as glycol and corrosion inhibitors in the tank. The content is circulated after adding. The tank is equipped with an electric pump for emptying and filling the cooling water circuits, a drain valve and an overflow pipe for venting the tank. It’s sized such that it can store entire water volume from the cooling water system. [29, 50]

4.3.3.2 Internal cooling water system (1-C)

The internal cooling water system of the EDG set consists of the following main components, which are shown in Figure 18 below:

- HT-cooling water pump;
- LT-cooling water pump;
- HT-charge air cooler (HT-CAC);
- LT-charge air cooler (LT-CAC);
- Lubricating oil cooler (LOC);

- HT-thermostatic valve.

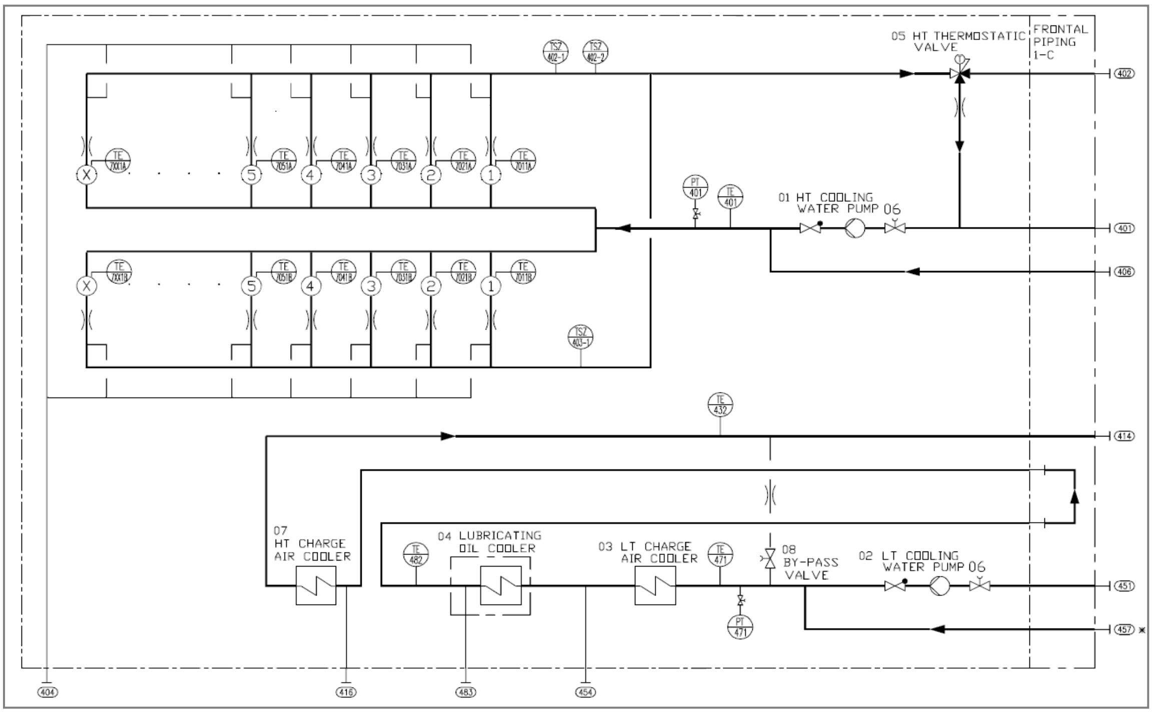

Figure 18: Flow diagram of typical internal cooling water system of EDG set (1-C configuration). [50]

Functions of internal HT- and LT-circuits

The main function of the internal HT-circuit is to cool down the engine jacket and cylinder heads as well as injection nozzle and exhaust valve seats. The secondary function of the internal HT-circuit is to maintain the engine jacket in pre-heated condition and to maintain HT-water temperature during operation. Inside the engine, HT-water flows through distributing ducts (casted in the engine block) to the engine jacket and to cylinder heads where it is forced to flow along flame plate, around the nozzle and the exhaust valve seats, cooling all these components. From the cylinder heads HT-water is led to a collecting duct where HT-water temperature is sensed by temperature switches. After the collecting duct, HT-water flows to a thermostatic valve that is integrated to outlet channeling of the HT-circuit. [35, 50, 51]

The function of the internal LT-circuit is to cool down charge air and lubricating oil by transferring heat from HT- and LT-charge air coolers (HT-CAC and LT-CAC) and lubricating oil cooler (LOC). LT-water flows first to the LT-CAC and then to the LOC. LT-water temperature is measured by a temperature sensor after LOC. Finally LT-water flows through the HT-CAC and a temperature sensor to the outlet of the LT-circuit. The LOC is described in Section 4.3.2.2, and both charge air coolers (HT-CAC and LT-CAC) are described in Section 4.3.4.2. [50, 51]

HT-cooling water pump

The pressure of HT-water and flow over the engine is maintained by a HT-cooling water pump. The pump is an engine driven centrifugal pump and is located at free end of the engine. After the pump, temperature and pressure of HT-water is measured by a temperature sensor and a pressure transmitter. [51]

HT-thermostatic valve

The function of the HT-thermostatic valve is to maintain HT-water temperature at a set point value, which is typically 96 °C for the outlet of the HT-circuit. The valve is a self-actuating, wax type, three-way valve and operates as a same principle as the LT-thermostatic valve. The HT-thermostatic valve is also equipped with manual override function that allows shutting off the by-pass line entirely. This provides maximum cooling for the engine jacket in case of malfunction of valves. [35, 50, 51]

LT-cooling water pump

The LT-cooling water pump maintains pressure of LT-water and flow over the engine. The pump is an engine driven centrifugal pump and is located at the free end of the engine. LT-water temperature and pressure is measured and monitored by a sensor and a transmitter after the pump. [50, 51]

4.3.4 Charge air system

The function of the charge air (or intake air) system is to provide clean and dry air to the engine combustion process in correct pressure and temperature. When the engine is operating, charge air to the engine is normally taken from outdoors through a charge air filter. After filtration, charge air flows along pipe system directly into a turbocharger (TC) or alternatively through a three-way damper and a charge air silencer. The TC compresses charge air and forces it into charge air coolers (CACs). After cooling, the charge air is led to a charge air receiver from where it is released into cylinder combustion process by means of inlet valves. [29, 35]

4.3.4.1 External charge air system

The external charge air system of the EDG set consists of the following main components outside the engine, which can be seen from Figure 19 and from Figure 20 below:

- Weather hood and louver (water droplet separator);
- Charge air filter;
- Charge air three way damper, actuator and back-up filter (optional);
- Charge air silencer and piping.

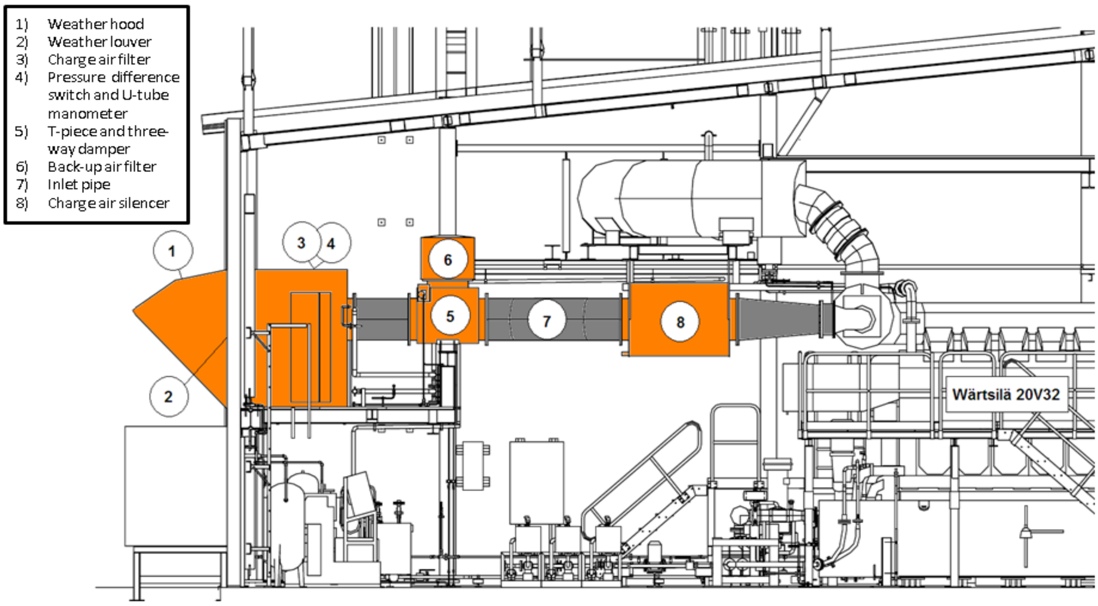

Figure 19: Cross-section picture of external charge air system (Wärtsilä 20V32 Oil Cube solution). [43]

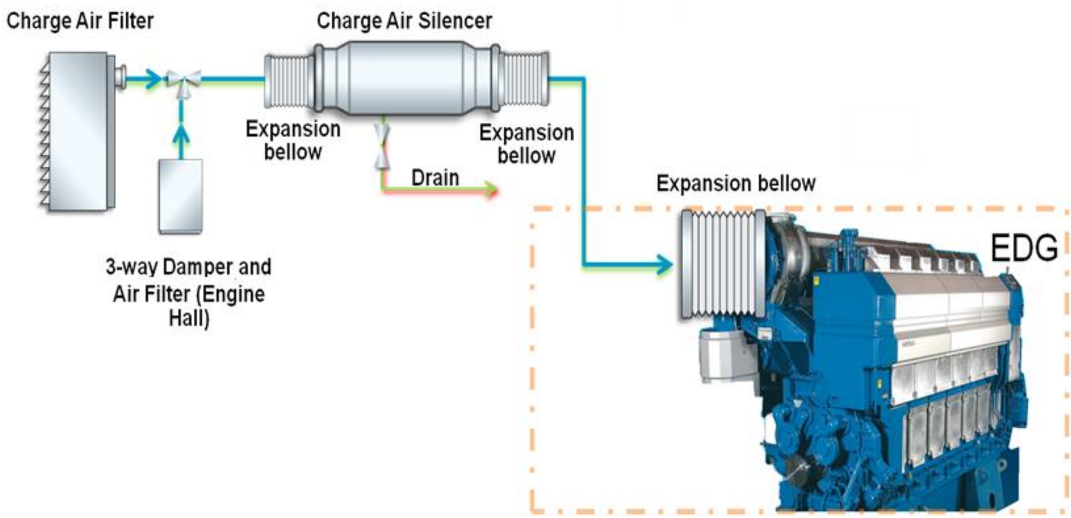

Figure 20: Schematic flow diagram of external charge air system of EDG set. [52]

Charge air filter

There are three different types of filters: dry type, oil wetted and jet pulse filters. The dry type filter is preferred solution for the charge air system of the EDG set due to its simple structure and suitability for stand-by applications. Therefore other filter types (oil wetted, jet pulse) are not described further. The dry type charge air filter consists of a one-stage dry bag filter. A filter unit comprises of a number of small pocket filter elements that are fixed into one box unit. The filter elements can be removed individually for replacing. The charge air filter is equipped with a differential pressure alarm that consists of a pressure difference switch and a U-tube manometer. [29, 35]

Weather hood and louver

Actual charge air filter unit is protected from varying weather and ambient conditions (rain, snow, insects, etc.) by means of a weather hood and a vertical louver. The vertical louver separates water droplets and protects the filter from being soaked. The weather hood protects the filter from direct rain. The louver can be also heated by means of electrical heating coils if ambient air temperature is near or below 0 °C to prevent freezing and ice formation in the filter structure. [29, 35]

Three-way damper, actuator, back-up filter (optional)

In case pressure drop over the charge air filter increases too much due to clogging or other reasons, charge air may be taken from inside the EDG room through a back-up air filter. This change-over is done by an electrically actuated three-way damper, and initiated by a pressure switch. The three-way damper is of a one-plate type and it's connected to an electrical motor driven actuator, which instead is controlled based on a pressure difference over the air filter. The assembly comprises also a coarse filter and a T-piece. The three-way damper is located inside the T-piece. The three-way damper is optional solution and can be selected in case the EDG plant is located in cold climate or areas subject to sandstorms. [29, 35]

Charge air silencer

Sound pressure level at the turbocharger charge air inlet is typically about 120 dB(A), High frequency noise is distributed by peaks of revolution speed of the turbocharger and its blade frequency. This noise is damped by a charge air silencer. The silencer is dissipative type and it is horizontally placed close to the turbocharger inlet. [29, 35]

4.3.4.2 Internal charge air system

The internal charge air system of the EDG set consists of the following main components, which are shown in Figure 21 below (the internal exhaust gas system and related main components are also shown in the figure):

- Compressor of turbocharger (one turbocharger per cylinder bank);
- Charge air coolers (LT-CAC and HT-CAC);
- Charge air receiver;
- Charge air waste gate valve (AWG).

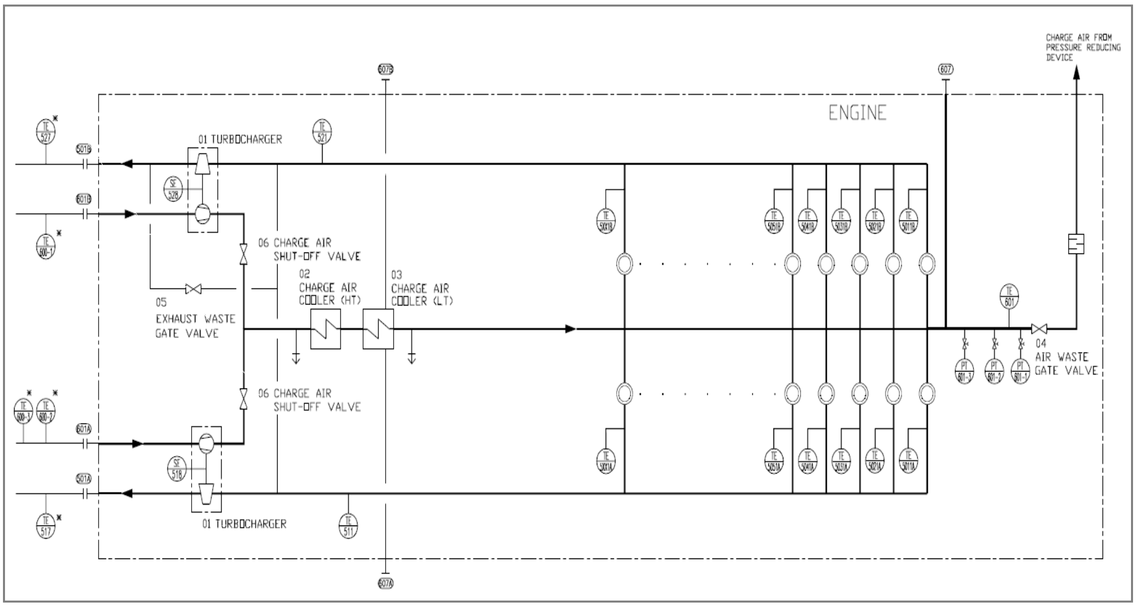

Figure 21: Flow diagram of typical internal charge air and exhaust gas systems of EDG set. [52]

Compressor of turbocharger

A turbocharger (TC) compresses charge air into higher density and increases power output of the engine by forcing charge air into combustion chambers of cylinders. In addition, efficiency of the combustion can be improved by utilizing heat energy of the engine exhaust gases into incoming charge air. Wärtsilä 32 V-type engine is equipped with two TC compressors (one per cylinder bank) whereas the in-line (L-type) engine has one TC compressor. The TC is mounted at free end of the engine with a flexible bellow connection to prevent vibrations to be transferred to external charge air piping system. The TC is of an axial turbine type that consists of an exhaust gas driven turbine with a centrifugal compressor mounted on the same shaft. The TC is equipped with speed sensors to count the turbine rotor blades during each revolution of the shaft. [29, 35]

Charge air coolers (LT-CAC and HT-CAC)

When the engine is loaded, temperature of charge-air increases in relation to pressure rise due to compression. Thereby charge air must be cooled to ensure that sufficient amount of air is supplied into the cylinders. Charge air is cooled in two-stages by the charge air coolers (LT-CAC and HT-CAC), which utilize LT-cooling water circuit. In first stage, charge air flows through the HT-CAC and in second stage through the LT-CAC before entering the charge air receiver. Additionally, charge air cooling can be used to heat intake air in case of cold ambient temperatures. [29, 35]

Charge air receiver and air waste gate (AWG) valve

The charge air receiver is integrated in the engine block and is located between the charge air cooler and the cylinder inlet valves. The charge air receiver can be equipped with an air waste gate valve (AWG) that is a pneumatically actuated globe valve. During normal operation of the engine, the AWG limits charge air pressure in the charge air receiver. The AWG limits also maximum firing pressure in the cylinders. When the engine operates at partial load, the AWG helps to avoid surge of the TC. The AWG is controlled by temperature sensors and is used especially in cold ambient conditions. [35, 53]

4.3.5 Exhaust gas system

The function of the exhaust gas system is to ventilate exhaust gases safely out from the engine to atmosphere as well as reduce the noise. When the engine is operating, exhaust gases are released out from each cylinder to an exhaust manifold. From the manifold, exhaust gases are conducted to the turbine of the turbocharger. Then exhaust gases are led out from the engine and the engine room through piping system. Outside of the EDG room, exhaust gases flow to an exhaust gas silencer that attenuates noise of exhaust gases before they are conducted to atmosphere through a stack pipe. [29, 54]

4.3.5.1 Internal exhaust gas system

The internal exhaust gas system of the EDG set consists of the following main components (a flow diagram of the typical exhaust gas system can be seen from the previous Figure 21):

- Exhaust manifold;
- Turbine of turbocharger;
- Exhaust gas waste gate (EWG) valve (optional).

Exhaust manifold
Exhaust gases from the cylinders are led by exhaust gas valves to an exhaust manifold that collects and conducts exhaust gases to the turbine of the TC. The manifold structure consists of exhaust pipes for each cylinder, steel bellows for absorbing thermal expansion and common multiducts for collecting exhaust gases. The complete manifold assembly is enclosed by an insulation box made of steel sheets. There are two types of exhaust manifolds, which are as follows: [29, 43]

- SPEX type manifold (Single Pulse Exhaust System);
- Pulse type manifold (3-Pulse System).

The temperature sensors are located after each exhaust gas valves in the cylinder specific ducting and at the turbocharger inlet and outlet. [54]

Turbine of turbocharger

The turbine of the TC is of an axial type. Exhaust gas flow from the manifold cause forced induction on the turbine. The speed of the turbocharger's turbine is measured by magnetic pick-up sensors that are mounted on a bearing space cover of the TC. The turbocharger (compressor side) is described in Section 4.3.4.2. [54]

Exhaust gas waste gate (EWG) valve (optional)

An exhaust gas waste gate (EWG) valve is a pneumatically actuated globe valve that can be used to limit charge air pressure in the cylinders and also to limit the speed of the TC. The EWG is located in the exhaust gas pipeline that by-passes the TC turbine. The EWG is opened when pressure in the charge air receiver reaches the predefined maximum value. Then part of exhaust gases passes by the turbine and flows to the exhaust gas outlet of the engine, in which case exhaust gas flow for the turbine is lower and less charge air is produced. [53]

4.3.5.2 External exhaust gas system

The external exhaust gas system of the EDG set consists of the following main components, which can be seen in Figure 22:

- Flexible bellows and exhaust gas piping;
- Exhaust gas silencer and stack pipe.

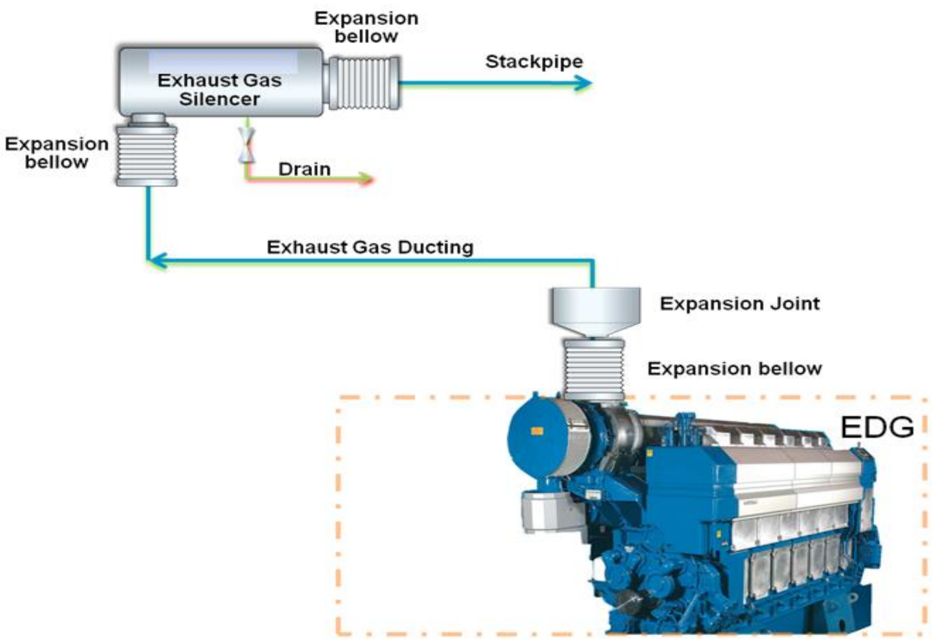

Figure 22: Schematic flow diagram of external exhaust gas system of EDG set. [52]

Flexible bellows, exhaust gas piping
Exhaust gases are led out from the engine and from the EDG room by an exhaust gas piping (ducting), which is connected to the outlet of the TC turbine by a flexible bellow (expansion bellow). In addition, the exhaust gas piping system outside the engine is equipped with several flexible bellows. These bellows allow thermal expansion and prevents vibrations from the engine to be transferred to the piping system. The whole piping is insulated inside and outside the EDG room. [29, 35, 54]

Exhaust gas silencer, stack pipe
Sound power level of exhaust gases is between 130 dB(A) and 150 dB(A) after the TC turbine. This noise is caused by dynamic pressure variation of exhaust gas flow. Exhaust gas noise is attenuated by an exhaust gas silencer that is located outside the engine room. Attenuation reduces noise approximately 35 dB(A) to 45 dB(A). The operation of the exhaust gas silencer is based on absorption, where exhaust gas flow passes through a perforated tube surrounded by sound absorbing material providing attenuation over a wide frequency range. The silencer is equipped with a drain pipe and it can be mounted either horizontally or vertically. The silencer is connected to a stack pipe (chimney) that discharges exhaust gases at required height. [29, 35, 54]

4.3.6 Starting air system

The starting air system and the instrument air system operate with compressed air, which means that both systems are called compressed air systems. However, typically these two compressed air systems are separated from each other and they don’t have any common components. Therefore the starting air and instrument air systems are described separately in the following chapters.

The engine of the EDG is started-up with compressed air. The function of the starting air system is to supply enough high-pressure air to the engine cylinders in order to start-up the engine successfully. The starting air system consists of two independent (redundant) starting air lines that distribute compressed air. Nominal pressure for the system is 30 bar and minimum pressure is between 10 and 15 bar depending on a configuration. [29, 35]

4.3.6.1 External starting air system

The external starting air system of the EDG set consists of the following main components, which are shown in Figure 23 below:

- Starting air compressor units (compressor, oil and water separator);
- Air dryers;
- Starting air bottles.

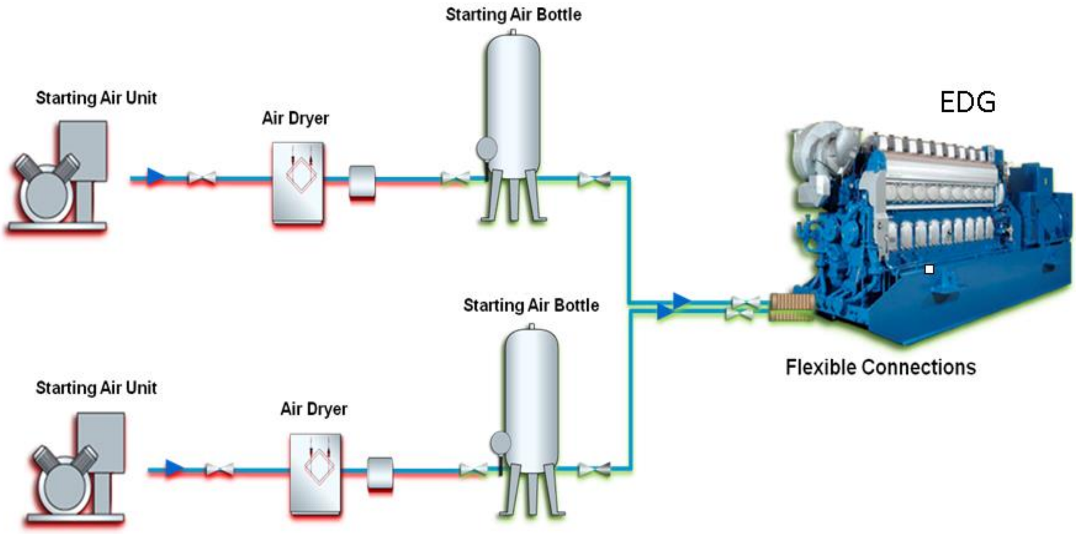

Figure 23: Schematic flow diagram of external starting air system of EDG set. [55]

Starting air compressor unit (compressor, oil and water separator)

The EDG is connected by two separate (redundant) starting air lines to starting air compressor units that compress air into high pressure and supply it to the engine along piping. The starting air compressor unit is mounted on a common steel frame, and normally it consists of one compressor and an oil and water separator. The unit is also equipped with a pressure control switch that automatically gives signals to the compressor to start if pressure in a starting air bottle decrease below required pressure level. The compressor is stopped by signals from the pressure control switch when required pressure is reached in the bottle. The compressors are of two-stage type, electrically driven and air-cooled. The oil and water separator is of a centrifugal type. The function of the separator is to remove water and oil from compressed air before drying. [29, 35]

Air dryer

An air dryer is located between the starting air compressor unit and the starting air bottle. The air dryer removes moisture from compressed air and keeps it dry enough to avoid corrosion in the piping and equipment downstream in the system. The air dryer can be of a dessicant type or a refrigeration type. [29, 35]

Starting air bottle

The starting air bottle is located between the air dryer and the engine. The function of the starting air bottle is to store compressed air and maintain pressure at required level. The bottle is equipped with a manual drain trap for removing any remaining moisture to avoid condensation in the bottle. [29, 35]

4.3.6.2 Internal starting air system

The internal starting air system of the EDG set consists of the following main components, which are shown in the following Figure 24:

- Main starting valves;
- Starting air valves;
- Starting air distributor;
- Air container;
- Pneumatic stop cylinders.

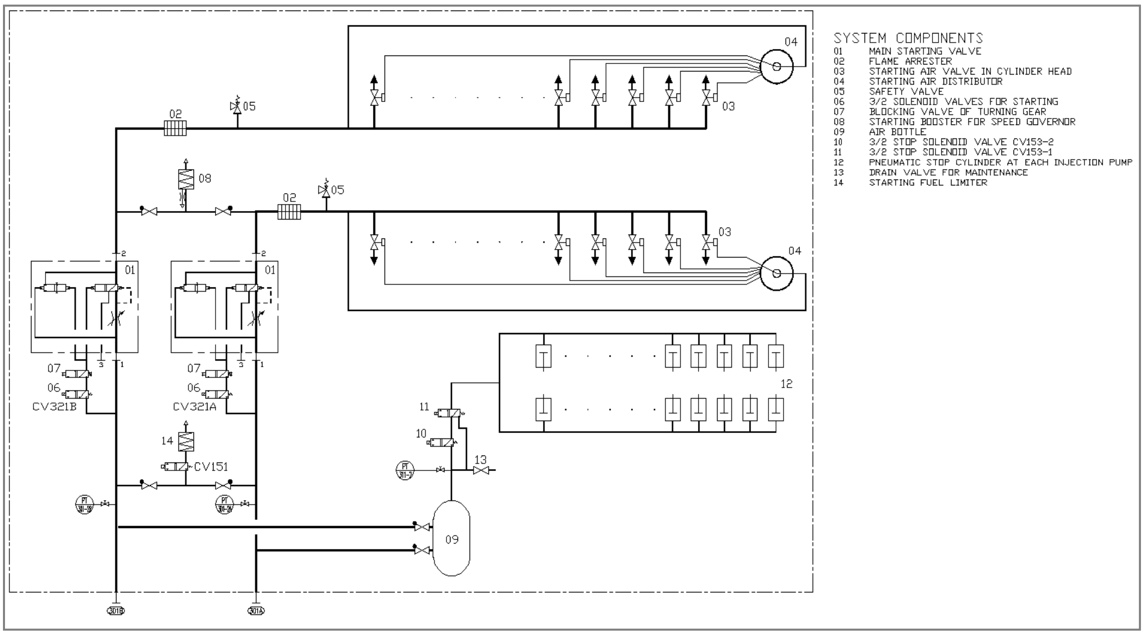

Figure 24: Flow diagram of typical internal starting air system of EDG set. [55]

Main starting valves, starting air valves, starting air distributor

The purpose of main starting valves is to admit compressed air to the internal starting air system. The main starting air valves can be electrically operated. They are located after starting air inlets of the engine. Air pressure at the air inlets before the main starting air valves is measured by pressure transmitters. When the engine start signal is initiated, start solenoid valves are activated automatically and main starting valves are opened. The solenoid valves can also be operated manually. After the main starting air valves are opened, air is led through flame arrestors to the starting air valves in the cylinder heads, which release compressed air sequentially into the cylinders. The starting air distributor controls that air is released in correct timing to the starting air valves. The starting air distributor is of a piston type and it is driven by the camshafts. [35]

Air container, pneumatic stop cylinders

An air container is a bottle that is pressurized in all operating conditions. It is located between the engine air inlets and pneumatic stop cylinders. The air container ensures that sufficient amount of air is always available for the main starting air valves. It actuates also pneumatic stop cylinders. The air supply line from the air container includes a pressure measuring transmitter for monitoring and trending air flow to the pneumatic stop cylinders. Non-return valves located at the air container inlet prevent return flow from the air container. The pneumatic stop cylinders are located in the engine fuel pumps. Their function is to cut LFO supply to the engine in case of emergency shutdowns. Stop solenoid valves release air flow to the cylinders. [35]

4.3.7 Instrument air system

The instrument air system supplies compressed air to pneumatically operated instruments and control devices mounted on the engine. Nominal pressure of the instrument air system is lower than in the starting air system being 7 bar. Main components of the system are actuated by instrument air. Typically the instrument air system of the EDG set is designed so that it's completely independent and not connected to the starting air system. However, connection between these systems can be arranged for back-up purposes. For example, a starting air compressor unit can be connected to the instrument air system to cover air supply in case an instrument air unit compressor malfunctions for some reason. [29, 35]

4.3.7.1 External instrument air system

The external instrument air system of the EDG set consists of the following main components, which are shown in Figure 25 below:

- Instrument air unit (compressor, air dryer);
- Instrument air bottle.

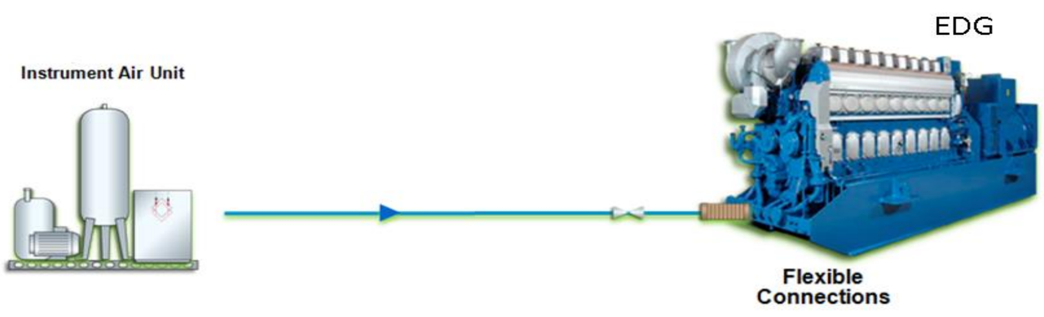

Figure 25: Schematic flow diagram of external instrument air system of EDG set. [55]

Instrument air unit (compressor, air dryer)
An instrument air unit filters, dries and compresses air into required pressure. The unit consists of a compressor, an air dryer and a filter built on a common steel frame. The compressor is a single-stage, air-cooled, screw type compressor. It’s equipped with a suction filter and a silencer. While the compressor is operating continuously, it’s controlled by an intake valve that opens and closes automatically. The air filter removes oil, water and other particles from compressed air before drying. The air dryer is of a refrigerant type, and its function is to remove moisture from air before entering the instrument air bottle. [29, 35]

Instrument air bottle
An instrument air bottle stores and maintains air pressure at required level. From the bottle compressed air is distributed along piping to instrumentation and control devices on the engine. The instrument air bottle is located on the same steel platform than the instrument air compressor unit. The bottle is equipped with a compressed air receiver and a manual drain trap for condensate drainage. [29, 35]

4.3.7.2 Internal instrument air system

The internal instrument air system of the EDG set consists of the following main components, which can be seen in Figure 26 below:

- Pneumatic actuators of AWG and EWG;
- Solenoid valve;
- IP-converters;
- Air container.

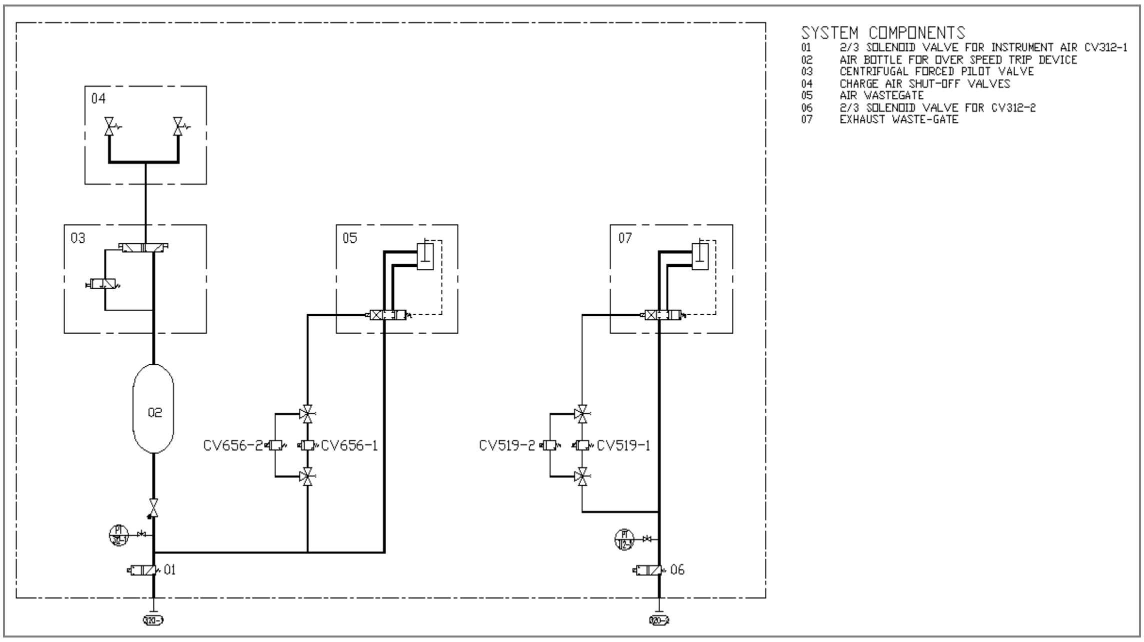

Figure 26: Flow diagram of typical internal instrument air system of EDG set. [55]

Pneumatic actuators of AWG and EWG

The charge air waste gate (AWG) and exhaust gas waste gate (EWG) valves are operated by pneumatic actuators. Functions of both waste gate valves are described in Sections 4.3.4.2 and 4.3.5.1. The pneumatic actuators are cylinders that are built-in to the AWG and EWG valves. The instrument air supply line is divided before the engine interface such that both waste gates have individual supply lines inside the engine. [29, 35]

Solenoid valve, IP-converters, air container

When the engine start signal is received, a solenoid valve opens and admits instrument air to the pneumatic actuators as well as to redundant IP-converters. Air pressure is measured by pressure transmitters before the pneumatic actuators. The IP-converters admit air flow to both waste gates. The instrument air supply line for the AWG valve includes also an air container bottle, which is an air reserve for the overspeed trip device and charge air shut-off valve. [29, 35]

4.4 Electrical and automation system

The electrical and automation system (E&A) is a combination of an instrumentation and control system (I&C) as well as an electric power distribution system. The function of the E&A-system is to monitor, control and protect the EDG system during operation and stand-by. The E&A-system provides fully automated control throughout at all operating modes.

The I&C-system can be remotely operated from the main control room and by the plant automation of the NPP. In addition, the I&C-system provides local operating interface and monitoring facilities of the EDG. The following descriptions and arrangements regarding to the I&C-system and power distribution system are based on Wärtsilä’s scope and solutions. Figure 27 below presents a schematic wiring diagram of the I&C system for the EDG system. [56]

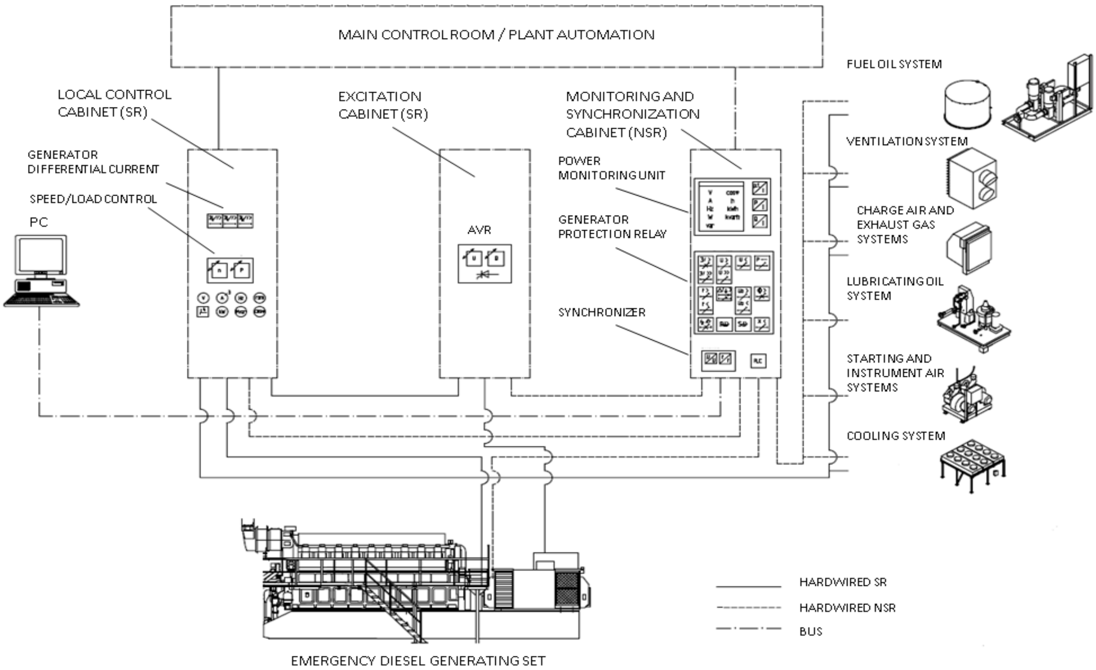

Figure 27: Schematic wiring diagram of I&C-system of EDG system. [57]

The I&C-system consists of different control cabinets (control panels) located in a local control room inside the EDG building, and field instrumentation such as sensors, switches, governors and actuators installed on the EDG set and on the auxiliary systems. From Figure 27 above, the control cabinets are organized as follows (typical solution, other configurations are possible):

- Local control cabinet (safety related);
- Excitation cabinet (safety related);
- Monitoring and synchronization cabinet (non-safety related).

These local control cabinets have different control logics as well as protection, regulation and monitoring functions. The electric power distribution system supplies low voltage (LV) alternating (AC) and direct current (DC) power to the EDG's electrical auxiliaries by means of a diesel backed bus bar from the NPP and LV switchgears. [56]

4.4.1 Control

4.4.1.1 Control logic

The control logic of the EDG system can be based on relay (analogue), digital or electronic logic. The analogue relay based control logic is typically used in control of the EDG due to its simplicity. The control system detects external inputs such as commands from the main control room (MCR) or measuring meters by means of control logic. The control system recognizes also ongoing engine mode to operate the entire EDG system in a proper way. This particular function is called a mode management. Furthermore, the control system operates the EDG system by using prioritization logic meaning that external inputs have certain ranking with lower or higher level priority. Lower priority signals are superseded by higher priority signals if these are coming at same time to the control system. For example, if the engine is not in emergency operation mode, it is working as a normal engine with normal protection functions based on prioritization logic. In emergency mode, all protection functions are available. The control panels also contains certain safety related (SR) and non-safety related (NSR) control devices. The SR control logic is required for automatic and manual start-up including emergency operation of the EDG system. [35, 56, 58]

4.4.1.2 Speed and load control

The speed and load control of the EDG is realized by means of several devices, which are mounted either on the EDG set or are located in vicinity with connections. An electronic speed control unit (speed governor) controls speed and load of the EDG, and a speed measuring device is used for indication. Typically the speed governor is of an analogue type (can also be digital) provides control either in isochronous operation mode or in droop operation mode, which both are adjustable.

In the isochronous operation mode the EDG will either run at no-load (idling) or in island operation supplying consumers of the diesel-backed switchgear via specific emergency bus-bars connected to the NPP. In both cases, the speed governor maintains the speed of the engine at a pre-set value (constant speed) to satisfy load demand as long as necessary. During the isochronous operation mode, all engine protection functions are active. [58, 59]

The droop operation mode is otherwise similar to the isochronous operation mode except now the EDG is synchronized with the off-site grid in the droop operation mode with pre-set droop value for testing purposes. The droop operation mode is always entered from the isochronous operation mode after synchronization action. Droop in a governing system of the engine is determined as change in speed that the EDG performs in moving from full load to idling (no-load) condition (speed decreases or diminishes in some proportion). In the droop operation mode, all engine protection functions are active. [58, 59, 60]

The electronic speed control unit sends signal to an engine-mounted actuator that actuates fuel pumps via a fuel rack during operation. The actuator includes a built-in topping ball back-up governor, which is operating in reverse acting principle. The actuator provides redundancy for the governing system in case of power loss to the speed control unit or loss of speed measuring signal. In these cases, the back-up governor takes control of the speed setting automatically. [35, 56, 58]

4.4.1.3 Voltage regulation (excitation)

The voltage regulation (excitation) of the EDG is realized by means of an excitation system and related devices such as an automatic voltage regulator (AVR) and its back-up module. In island operation mode, the excitation system controls excitation field of the generator's exciter in isochronous mode as required to maintain the stator voltage within allowable limits during loading sequences and steady conditions. In parallel grid connection mode (EDG is synchronized with the off-site grid), the AVR is operated in voltage droop mode with selected droop settings. Voltage regulation modules are of a solid-state type and designed to operate with brushless excitation systems and a permanent magnet generator (PMG). The excitation cabinet is powered with the PMG. Feedback signals are wired from the generator's current and voltage transformers that are located at the generator terminal box or at the EDG switchgear. [35, 56, 58]

The AVR regulates output voltage (terminal voltage) and reactive power from the generator according to chosen power control mode and set values. The output voltage is regulated by controlling DC field current in the rotor windings (field excitation). The AVR observes changes in the generator's terminal voltage (i.e. caused by a sudden load change) and varies field excitation as required to restore output voltage or reactive power of the generator. The excitation is automatically switched on and off at a specified engine speed. [29, 35, 61]

During normal and steady loading conditions, the AVR maintains a constant and a stable generator output voltage within specified tolerance limits of the set value (± 1 %). Typically the operating range of the generator is ± 5 % of nominal voltage and the control range of the AVR is ± 10 % of the nominal voltage. Available automatic power control modes for the AVR are a power factor mode and a voltage droop control mode. Also a field current mode (manual excitation mode) is available as a back-up for automatic control modes. [29, 35, 61]

Limiting functions encompassed in the AVR are used during test runs. The correct operation of the excitation system (i.e. operation of the AVR, measurement circuits and diode bridge) is monitored by failure detectors. In case the AVR fault or trip of measurement voltage transformer's miniature circuit breaker (MCB), the AVR will change-over to a redundant control module (back-up module) automatically. Bumpless control transition between regulators is ensured with an automatic voltage balancing circuit. [35, 56, 58]

4.4.1.4 Control modes of speed and voltage regulators

During island operation, the speed regulator and the AVR provide constant frequency and generator voltage in isochronous mode. In parallel operation with grid, adjustment of speed and voltage settings affects the EDG's active and reactive powers with chosen droop settings respectively. Isochronous and droop modes are determined on the basis of the grid circuit breaker (CB) position. [56]

4.4.1.5 Signal filtering, conversion and measurement

The purpose of the signal filtering is to eliminate undesired parts (low or high pass) or to extract desired parts (band pass or stop) of the signal. Undesired parts of a measured signal could i.e. be random noise and desired parts of a signal could be i.e. special signal components in a certain frequency range. As for the EDG, this means that the signal filtering is eliminating undesired parts of the signal that might create false alarms or other undesired effects. In the design of automation of the EDG, it must be taken account that some signals of the EDG require filtering. Figure 28 below shows the philosophy of the signal filtering. [56]

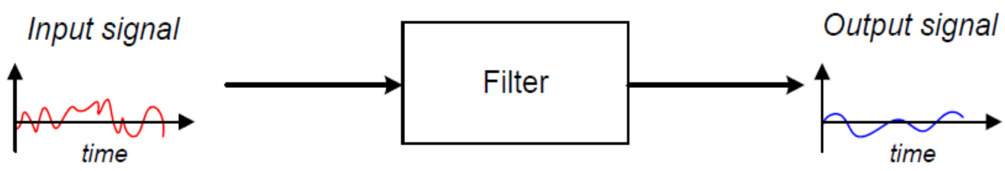

Figure 28: Philosophy of signal filtering. [56]

4.4.1.6 Manual control interface

The manual control interface of the control system is realized by means of various operating switches, push-buttons, meters and signal lamps, which all are located on the local control cabinets. [56]

4.4.1.7 Synchronization

The EDG can be synchronized with the electricity grid mainly for testing purposes and to return off-site power supply after black-out. The EDG synchronization can be commenced either manually or semi-automatically from the synchronization and monitoring cabinet in the local control room, standby control room or the main control room. Synchronization can be monitored from all locations. Synchronizing equipment shall be able to synchronize both a generator breaker and a grid breaker to an energized diesel backed bus bar (MV- or LV- switchgear). [29, 35]

Synchronizing equipment consists of an automatic synchronizer and a synchrocheck relay, and these devices are physically placed into the synchronization and monitoring cabinet. Neither of the devices is active during emergency start when connecting diesel to a de-energized diesel backed bus bar. The automatic synchronizer compares output frequency and voltage from the generator to frequency and voltage of the EDG bus bar, and adjusts the engine speed and the generator excitation to equalize them. [35, 56]

4.4.2 Protection

The protection of the EDG system consists of protection instrumentation such as electrical protection relays of the generator, sensors and switches for monitoring the engine and auxiliary systems as well as fuses in the switchgear. All related trip functions from the protection instruments are wired through the local control cabinets and collected into a trip matrix. [35, 56, 58]

The protection instrumentation consists of safety related (SR) devices, which are active during an emergency operation, and non-safety related (NSR) devices that are active during test-runs (i.e. during parallel operation with the grid). During an emergency operation, the NSR devices are sending only alarms and notifications, while the SR devices are controlling essential safety functions for which use the EDG is designed for. In order to avoid false trip signals, all protection functions of SR devices are monitored by three identical safety devices, and the EDG shutdown signal is working according to the 2-out-of-3 principle. Connections of these protection devices are arranged such that possible cable breaking indicates only alarm signal and does not activate any safety function. All alarms and some status indications are displayed at the local control cabinets, and collection of alarms will be send to the main control room. [35, 56, 58]

The SR protection on the engine consists of an engine overspeed, high HT-water temperature and low LO pressure. All these SR functions initiate the engine trip even if the EDG is operating in emergency mode to prevent breakdown. For the generator the SR protection consists of the generator overcurrent and differential current measurement. For the auxiliary systems, the protection is achieved by means of different switches and related equipment that monitor and measure i.e. surface levels, pressures and temperatures. The electrical power distribution system's protection consists of i.e. fuses, miniature circuit breakers (MCBs), overload relays. [17, 28, 56]

4.4.3 Engine monitoring

All measured signals from the engine are available in the local control room on local operator station through monitoring, protection and synchronization cabinet. An engine monitoring panel is a local display panel located in the engine room next to the EDG, and its purpose is to display only limited amount of signals concerning the engine for machine operators for test runs. [56]

Monitoring circuits are separated from SR devices and circuits. Amongst other things, the engine monitoring panel and interface have typically at least the following local monitoring features: local displays, alarm panels, trend displays, process displays, event lists, data logging (slow, semi-fast), transient recorders (fast), time stamping, data synchronization and bus-protocols. [56]

The operation and performance of the EDG is monitored and visualized with the help of a computer based Human-Machine-Interface (HMI), which is typically tailored design depending on the customer requirements. Short term and on-line supervision features of HMI includes process displays that are graphical pictures showing continuously measured values and status indications about the generating set. The events of the EDG are shown in the event list, which includes data logging values (slow or semi-fast event) and transient record values (fast event). A trend display is available for analogue values of the EDG. In addition to this, the EDG normally has a workstation that displays trends of production, long and short term data for diagnostic purposes, and engine condition follow-ups. The workstation connects to different systems in the plant via a network interface to collect data for analysis. The workstation displays technical and production reports, logbooks and applications. [56, 62, 63]

However, because the EDG differs from a conventional generating set especially concerning the I&C-system, the operator HMI most likely has to be different. Typically the EDG monitoring interface is more or less tailored design with some variations and specific features, because information required differs in many ways from regular solution. [12]

4.4.4 Power distribution system

The control system of the EDG is interconnected with the power distribution system that comprises supporting electrical systems of the NPP such as a diesel backed bus bar, LV AC supply and LV DC supply systems. Typically there are two alternatives how the power distribution system can be arranged by the EDG supplier in order to meet the customer expectations. These two options are illustrated in Figure 29 below. [12, 56]

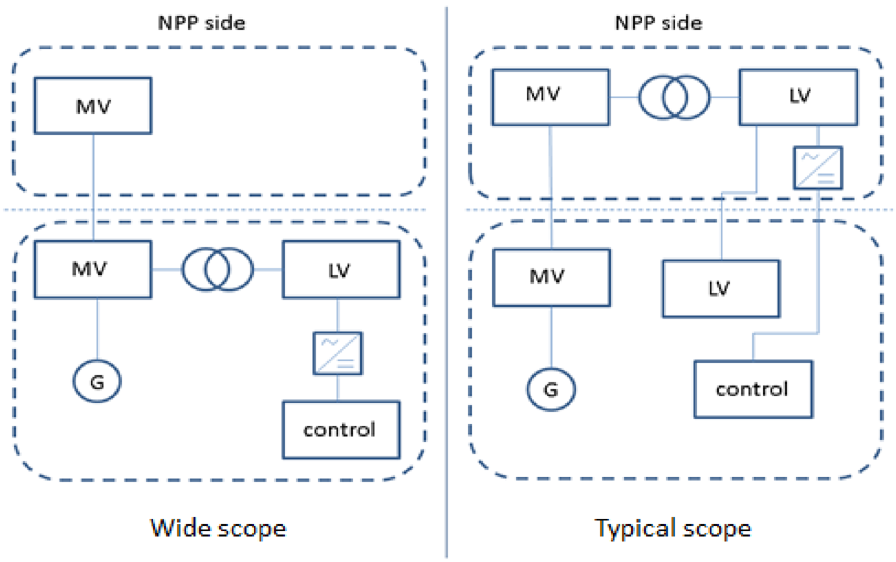

Figure 29: Simplified drawing of power distribution system alternatives (wide scope on left side and typical scope on right side). [12]

4.4.4.1 Diesel backed bus bar

The EDG is connected to an isolated diesel backed bus bar that conducts mainly medium voltage (MV) electricity from the EDG to the NPP. The design of this depends on the NPP's architecture and is not in Wärtsilä's scope. [56]

4.4.4.2 LV AC supply

LV AC power (660 V AC) is distributed to EDG specific auxiliaries during operation and stand-by mode from LV switchgears. Typically the switchgear is automatically operated from the local control cabinets. However, manual operation of individual feeders is possible with help of selector switches located in the local control room. Motor feeder terminals of the switchgear consist of fused switch, contactor, thermal protection relay and operation indication lights. The switchgear also contains voltage and current meters to indicate currents and voltages of all phases. Characteristics of fuses and thermal protection relay are chosen to ensure correct clearance of faults. The switchgear has hardwired signaling interfaces with control and trip signals as well as annunciation and alarms. [56]

There are three switchgears that distribute power. The first LV switchgear distributes AC LV power supply from diesel backed emergency switchgear to SR electrical auxiliaries of the EDG. The second LV switchgear feeds such SR and NSR consumers (loads), which are required or preferable to have an extended operation in various operating conditions. This switchgear is supplied also from the diesel backed emergency switchgear. Lower safety class of the switchgear and consumers is taken into account in selectivity of the feeder protection. The third LV switchgear feeds NSR consumers that are available during stand-by and maintenance of the EDG. This switchgear is supplied from a LV AC supply (NSR) without diesel back-up. [56]

4.4.4.3 LV DC supply

The battery-backed DC system of the NPP as well as the EDG specific DC system supplies both SR and NSR consumers (devices) of the EDG control system with DC auxiliary power (typical value is 110 V DC, but also 220, 48 and 24 V DC are possible). Battery systems are separated from each other with isolation diodes if the feeding is from two systems. The engine related instrumentation is supplied with 24 V DC auxiliary power converted from 110 V DC supply with two parallel-coupled DC/DC converters. [56]

Different safety classes of the consumers (SR or NSR) are taken into account in short-circuit and overload protection. DC supply to SR and NSR consumers is a requisite for full functionality of control, protection and monitoring devices. An automatic start and subsequent operation can also be commenced with limited DC supply only to SR control gear. In case of a black-out in the reserve power AC switchgear, only battery backed DC supply for SR control systems is required to enable reliable start of the EDG. [56]

4.4.5 Field instrumentation

The control system has interconnections to field instrumentation consisting of various sensors, switches and actuators located on the EDG set, on the auxiliary systems of the EDG and the ventilation system of the EDG facility. Position and fault indications for control purposes as well as critical alarms and protection functions are realized with “normal open” (NO) contacts, whereas alarm signals with “normal closed” (NC) contacts. Monitoring signals are either obtained from transmitters, or in case of temperature detection, measured directly from PT100 type resistance temperature detectors (RTDs). The actuators are typically on-off type (i.e. solenoids) with a few actuators as an exception (i.e. speed regulator). The instrumentation is connected to control cabinets so that the local control cabinet includes control signals, tripping signals and sum-alarms, and the monitoring and synchronization cabinet includes measurement signals, status indications and status alarms, and certain control and protection signals that will be inhibited during emergency operation. [56]

5 EDG PERFORMANCE AND OPERATION

5.1 Overview

The focus of this chapter is to investigate performance requirements and operation features of the EDG system when it is operating as an emergency power supply system with the NPP. The following topics are examined in this chapter:

- Safety functions;
- Starting and loading;
- Ratings and operating limit values.

The main sources of applicable criteria examined in this chapter are technical standards KTA 3702 and IEEE 387. Both standards are introduced in Section 3.3.1. In addition to these, NRC RG 1.9 (U.S. Nuclear Regulatory Guide 1.9, Application and Testing of Safety-Related Diesel Generators in Nuclear Power Plants) is used as an reference within this chapter. NRC RG 1.9 discusses e.g. about the EDG safety functions and clarifies the functional behavior of the EDG while it is subjected to starting and loading on supplied emergency loads of the NPP. NRC RG 1.9 supplements and guidelines also certain EDG design considerations as well as provides clarifications for testing criteria originally stated in IEEE 387. [64]

5.2 Safety functions

There are three fundamental and vital performance related functions that every EDG system selected for the service as an on-site emergency power supply in the NPP must accomplish under predefined conditions. These “duties” are called safety functions (or safety missions) as follows:

- Start-up;
- Accept load;
- Maintain load.

According to NRC RG 1.9 together with IEEE 387, every EDG selected for use as an on-site electric emergency power supply system for the NPP shall have the capability to start-up, accept load and accelerate a number of large motor loads in rapid succession (sequence), while maintaining voltage and frequency within acceptable limits. The EDGs must also be able to provide power rapidly to the NPP’s engineered safety features (ESF, emergency power supplied loads, safety auxiliaries) in case of a LOOP event or/and a design-basis event (DBE) occurring during the same period of time. In addition, the EDGs must supply power continuously to the equipment needed to maintain the NPP in safe condition as long as necessary (i.e. for duration of several days until normal power supply from the off-side grid is restored for example in case if an extended LOOP occurs). [3, 28, 64]

For clarification, it is important to notice that shutdown of the EDG is not considered as a safety function similarly like abovementioned three safety functions. The shutdown of the EDG is performed only by means of predefined safety principles (2-out-of-3 protection logic), which shall not jeopardize the emergency power supply to the NPP's engineered safety features (ESFs) while experiencing a LOOP or/and DBE. [12]

5.3 Starting and loading

5.3.1 Starting time

Basically, the starting time of the EDG is considered to be a time period between a start signal emitted from the NPP main control computer and availability for load acceptance of the EDG. The required start-up time for the EDG is depending mostly on the NPP reactor design. Many of the reactor designs (i.e. LWR type reactor) demand emergency power to be available within 15 to 30 seconds after the EDG receives a start signal. This time period includes an inherent delay for protective circuits to sense the loss of power from the off-site grid (e.g. LOOP event) and initiate a start signal to the EDGs. In addition, inside this start-up time period, necessary functions are to spin up the EDG generator, energize it, and switch it on-line. [3, 28, 64, 65]

For ensuring an acceptable safety margin, many accident analyses for LWR reactor designs have assumed that emergency power from the EDGs should be available within 10 to 15 seconds (typical time frame required by the customer is 10 - 20 seconds). This so called fast start requirement set certain challenges for the engine and the generator. As an example, challenges for the engine are overshooting and incomplete combustion process due to lack of air, which means that fuel injection needs to be typically limited until very end of the ramp-up. On the other hand dimensioning of the generator for loading capability (high inertia demand) is in contradiction with short start-up time. [3, 28, 64, 65]

5.3.2 Emergency mode starting sequence

Actions of a starting sequence depend on the nature of the required operation mode, as an example whether the EDG system shall operate in the emergency operation mode or in the test operation mode (isochronous or droop operation mode). Next description will briefly clarify basic functions, which happen within this required start-up time period when the EDG is started to operate in the emergency operation mode after receiving start-up signal. All these functions are supposed to happen approximately in 10 to 20 seconds. In normal situation, the EDG is in the stand-by mode meaning that the unit is ready to operate instantly by means of facilitation functions such as pre-heating and pre-lubricating the engine. Temperatures and pressures of operating media (fuel, lubricating oil and cooling water) in the engine are at sufficient level to ensure successful and fast start-up.

The control system of the EDG recognizes the start-up signal, and measures condition of the unit at the same time. Alarms and faults in the EDG and in auxiliaries that are not supposed to trip the EDG for protective reasons, will be bypassed. The control system initiates the starting air system to supply air into the engine cylinders in correct pressure and timing. The air vessel of the starting air system shall be sized appropriately so that air pressure can be maintained at proper level and required amount of starting attempts can be provided. Eventually the cylinders crank the engine at low speed to enable normal firing in the cylinders. While the engine speed is increasing, the generator starts to energize its field in equal proportion to achieve rated voltage and frequency. After gaining the acceptable limit values of voltage and frequency, the EDG is ready to accept load, and safety-related loads of the NPP are connected to the EDGs' isolated bus bars in predefined sequence order. [3, 65]

5.3.3 Transient and steady-state threshold values

The transient phenomenon means a situation where a certain controlled parameter (e.g. frequency, terminal voltage or speed) deviates momentarily from the desired value. Typically this phenomenon is a result of the EDG start-up or connection/disconnection of the EDG supplied loads. Steady-state limits encompass an area where controlled parameter is maintained during steady-state operation after the EDG has been recovered from the transient situation. The steady-state threshold values are determined in relation to prevailing set-point values of the controlled parameter. This means that a specific safety margin is always added to the set point values to ensure that fluctuation phenomenon of frequency, voltage or speed will not exceed maximum limits (tripping limits) easily. [66]

Figure 30 below shows typical values and limits of the transient and steady-state thresholds that can identified for the EDG. It also illustrates how the controlled parameter typically behaves when the EDG is started or EDG-supplied loads are connected or disconnected. In addition, definitions of these threshold values and limits seen in Figure 30, are explained in Table 7 below. [66]

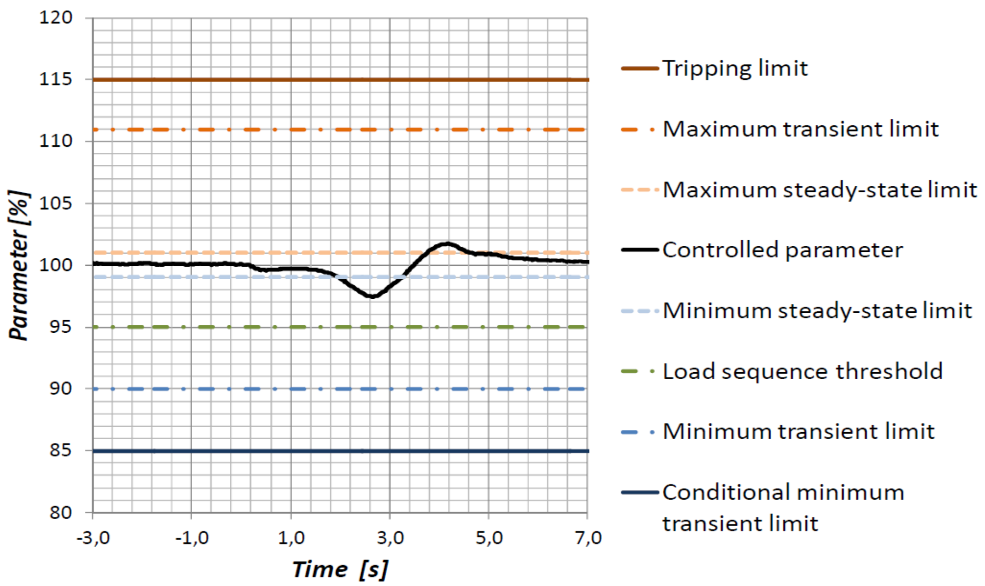

Figure 30: Illustration of transient and steady-state threshold values for the EDG. [66]

Table 7: Definitions of transient and steady-state threshold values for the EDG. [66]

Transient and steady-state threshold values for EDG	
Limit	**Definition**
Conditional minimum transient limit	• Lowest momentarily allowed value of controlled parameter. • Applicable in certain predefined transient situations such as start of a large electric motor or during the first load step of the EDG set's loading sequence.
Minimum transient limit	• Lower boundary of an area to which controlled parameter is allowed to decrease for a specified time (recovery time) during typical load transients.
Load sequencer threshold	• Project specific value which is agreed with the customer. • Release signal will be issued to load sequencer when controlled parameter has reached this value at start-up and load sequencer connects load to EDG-supplied switchgear based on predefined loading sequence.
Minimum steady-state limit	• Controlled parameter is required to be maintained above this limit during steady-state operation of the EDG set.
Maximum steady-state limit	• Controlled parameter is required to be maintained below this limit during steady-state operation of the EDG set.
Maximum transient limit	• Upper boundary of an area to which controlled parameter is allowed to increase for a specified time (recovery time) during typical load transients.
Tripping limit	• If controlled parameter exceeds this limit, a delayed or instant trip of the EDG set will occur.

5.3.4 Readiness for load acceptance

In practice the EDG's readiness for the load acceptance is achieved when both frequency and terminal voltage of the EDG generator have reached a minimum steady-state limit or a load sequence threshold value. However, in order to maintain certain safety margin to tripping limit, the controlled parameter (frequency, voltage and speed) should not exceed maximum transient limit. Like mentioned earlier, the EDG shall achieve the required voltage and frequency within the time frame of 10 to 20 seconds depending on the NPP reactor design. For clarifying more of this readiness for load acceptance as well as the starting time evaluation of the EDG, Figure 31 below shows in principle the behavior of the EDG generator's output frequency during start-up. [66]

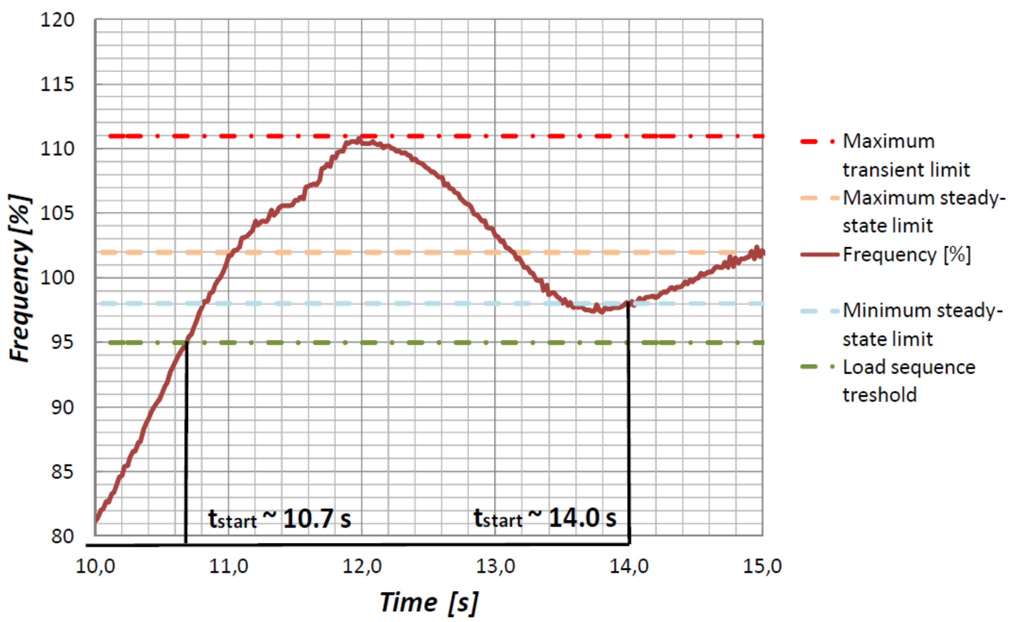

Figure 31: Example of frequency behavior and starting time evaluation of the EDG. [66]

5.3.5 Loading recovery times

The acceptable long-term and short-term deviations as well as the recovery times of voltage and frequency of the EDG are defined in technical standards (e.g. KTA 3702 and IEEE 387) or in project-specific technical specifications. The long-term tolerance band or the steady-state band determines an acceptable operating range, which is not harmful to the EDG or to the EDG-fed consumers. The short-term limits define boundaries wherein operation for a limited duration of time is allowed and provided such that voltage and frequency are recovered back into the steady-state situation. [66]

The required loading recovery times vary depending on the specification source (standard or technical specification). For example, NRC RG 1.9 defines the recovery time to be 60 % of the loading sequence interval, which practically means that the recovery time can vary between 3 to 6 seconds for 5 to 10 seconds intervals respectively. The purpose of these loading recovery times is to ensure that the EDG's frequency and voltage are stabilized for further load steps. The definition for the recovery time by Wärtsilä and based on KTA 3702 is a period of time between maximum load application or load release to final recovery back into the steady-state boundaries of the controlled parameter. Figure 32 below shows an example of this loading recovery situation, when an asynchronous electric motor (safety-related load) is started by the EDG. [66]

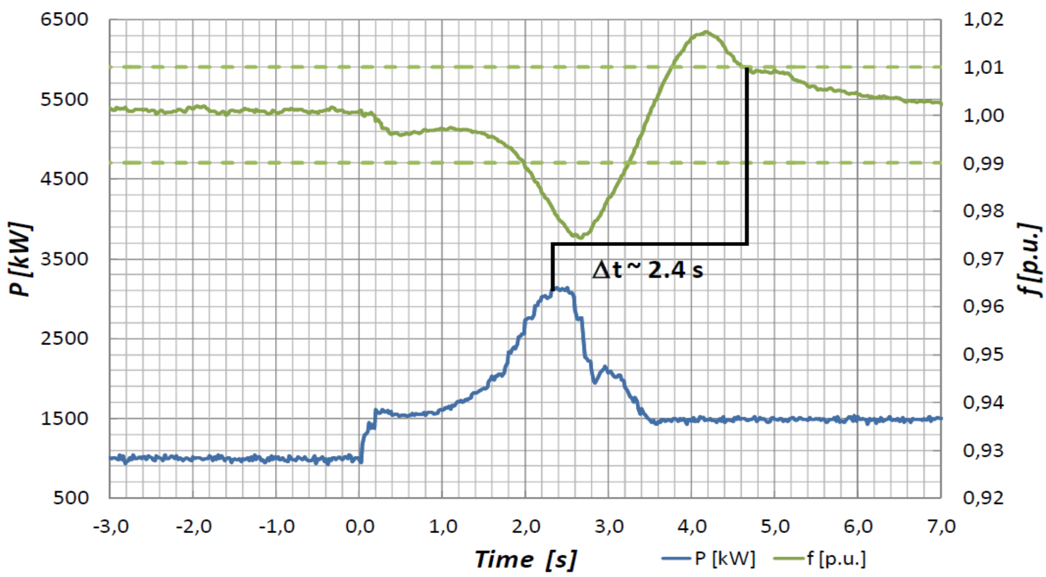

Figure 32: Example of loading recovery of the EDG caused by the starting of an asynchronous electric motor. [66]

5.3.6 Load profile, load types and load steps

Based on NRC RG 1.9 and IEEE 387 definitions, the load profile shows the magnitude and duration of applied loads in a predefined time sequence, including the transient and steady-state characteristics of the individual safety-loads for the most severe conditions, and including both automatically and manually sequenced loads. Typically loads are mostly applied to the EDG in a combination of block loads, which are sequenced to best match the design objectives of the NPP. It is important to have knowledge of the characteristics of each load to establish the bases for selection of the EDG. However, the customer often requires that the EDGs (i.e. sizing of the engine and the generator) are already specified in the early design stage, before the actual characteristics of the loads and an accurate load profile are known. [28, 64]

NRC RG 1.9 also discusses that normally the majority of these loads that the EDGs shall be able to accelerate in rapid succession (EDG-supplied loads), are large induction motors. This type of large motor, at maximum voltage, draws a starting current of 5 to 8 times its rated full-load current. As a result of the start-up of these induction motors, the sudden and large increases in current drawn from the EDG can cause substantial voltage reductions. This decreased voltage could prevent a motor from starting (i.e. accelerating its load to rated speed in the required time), or could cause a running motor to coast down or stall. Other voltage-sensitive loads might also be lost, because of low voltage or if their associated contactors drop out. [64]

For the EDGs, recovery from the transient caused by starting large motors, or from the loss of a large load, could cause the engine overspeed that (if excessive) might result in a trip of the engine (leading to a loss of the safety-related on-site power source). These similar adverse consequences can also result from the cumulative effect of a sequence of more moderate transients, if the system is not able to recover sufficiently between subsequent load steps within the loading sequence. [64]

The load step in the load profile signifies the power load difference, which results after each individual load or block of loads are applied to the EDGs' feeding. Based on IEEE 387 definition for the start and load acceptance tests and for the margin tests, the EDG must have capability to accept a single-step load of at least 50 % of the continuous kW rating. The load may be totally resistive or a combination of resistive and inductive loads. Basically, the EDG must have capability to start and carry loads that are greater than the magnitude of the most severe step load within the design load profile of the NPP. This includes step changes above the base load also. The limiting case for step changes over base load is not necessarily the largest step change, but may be a smaller step change as the full-load capability of the EDG unit is approached. [28, 64]

The requirement that the EDG shall accept a single-step load equal or above 50 % of rated load can be very demanding to achieve especially in the case where this 50 % of rated load is applied to the EDG's feed for the first step of the loading sequence. In this load acceptance case, the delimiting factor is practically the turbocharger's performance. If there is no sufficient flow in the turbine prior to and during the transient, this may cause stalling of the compressor. Additionally, inertia of the EDG set plays essential role, when the EDG needs to survive large load applications. Proper dimensioning of the EDG set ensures that the unit has enough inertia to survive large load applications. However, often the most severe step load based on the NPP's load profile should be applied approximately in middle section of the loading sequence due to safety reasons, and the EDG will not fall into the engine overspeed or other undesired situations. Figure 33 below shows an example of the load profile (theoretical profile) for the EDG-supplied NPP safety auxiliary loads. [12, 64]

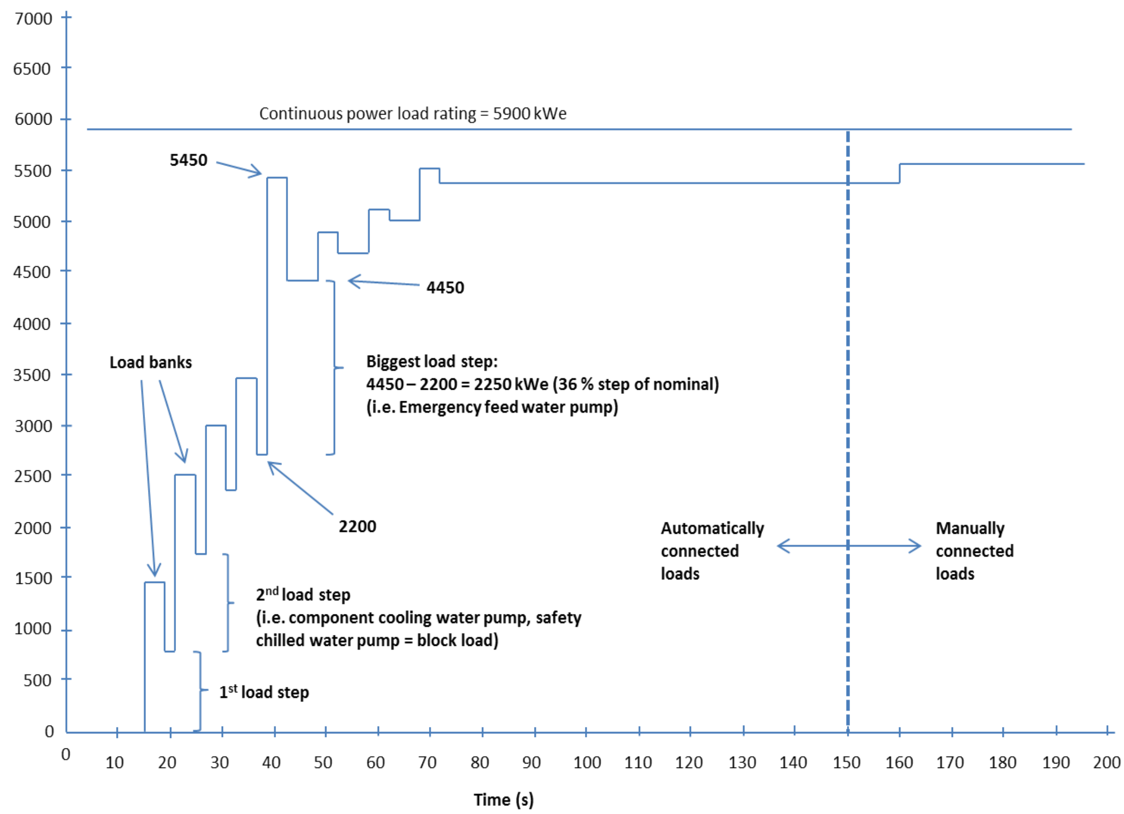

Figure 33: Example of theoretical load profile for the EDG-supplies loads (NPP safety auxiliaries, engineered safety features ESF).

5.4 Load ratings and operating limit values

This section introduces the main load ratings and operating limit values relevant to the EDG based on definitions and requirements stated in KTA 3702, IEEE 387 and NRC RG 1.9. The following topics are explored within this section:

- Static and dynamic tolerance values (KTA 3702);
- Start and load accepting capabilities (IEEE 387, NRC RG 1.9);
- Continuous load ratings and safety margins;
- Overload (short-time load) rating;
- Low-load (light-load) and idling (no-load) operation;
- Vibration during operation.

5.4.1 Static and dynamic tolerance values (KTA 3702)

According to KTA 3702, inside the static operating range (steady state operation, stable load) of up to 100 % rated continuous power of the EDG, the static tolerances for speed and voltage characteristic values shown in Table 8 below shall not be exceeded. Table 9 shows the permissible dynamic tolerances of speed, frequency, and voltage characteristics that shall not be exceeded under consideration of transient situations when the EDG is loaded (loads are connected) or unloaded (loads are disconnected). In addition, in the case of power load changes up to the overload power capacity (at least 110 % of the rated continuous power), the dynamic tolerances of the speed and voltage characteristics presented in Table 9 shall not be exceeded either. [17]

Table 8: Static tolerances for speed and voltage based on KTA 3702. [17]

Static tolerances (acc. KTA 3702)			
Characteristic value (relative to the nominal value)	**Symbol**	**Unit**	**Value**
Range of speed adjustment	-	%	+ 2.5 to – (2.5 + δ_s)
Static speed adjustment (P-degree)	δ_s	%	4 to 5
Static width of frequency variation	β_f	%	± 1
Voltage control range	ΔU_S	%	+ 5 to - 5
Voltage accuracy	σ_G	%	± 2.5

Table 9: Dynamic tolerances of speed, frequency and voltage based on KTA 3702. [17]

Dynamic tolerances (acc. KTA 3702)			
Characteristic value (characteristic percentage values are relative to the nominal values)	**Symbol**	**Unit**	**Value**
Dynamic speed deviation			
Maximum transient frequency increase	$f_{d,max}$	%	< 15
Maximum transient frequency decrease (frequency undershoot)	$f_{d,min}$	%	≤ 10
Triggering speed of the overspeed protection equipment	$n_{d,0}$	min^{-1}	≤ 1.2 n_N
Frequency adjustment time			
Release of maximum load level	t_{nE}	s	≤ 2
Application of maximum load level	t_{nB}	s	≤ 2
Frequency tolerance band	α_n	%	± 5
Dynamic voltage variation at generator terminals (under consideration of start-up currents of asynchronous motors, however without transient direct current elements)			
Transient voltage deviation during power level decrease (+)	σ_{DE}	%	≤ 20
Transient voltage deviation during power level increase (-)	σ_{DB}	%	≤ 15
Voltage adjustment time			
Release of maximum load level	t_{UE}	s	≤ 1
Application of maximum load level	t_{UB}	s	≤ 1

5.4.2 Start and load accepting capabilities (IEEE 387, NRC RG 1.9)

Based on NRC RG 1.9 and IEEE 387 definitions, the following frequency, voltage and speed tolerance values shown in Table 10 shall be considered when the EDG is started, loaded and loads are disconnected (load rejection).

Table 10: Start and load accepting capabilities based on NRC RG 1.9 and IEEE 387. [28, 64]

Start and load accepting capabilities (acc. NRC RG 1.9 & IEEE 387)			
Characteristic value	**Symbol**	**Unit**	**Value**
Frequency decrease (max) of nominal • at any time during loading sequence (1)	$f_{dec,max}$	%	< 5
Voltage decrease (max) of nominal • at any time during loading sequence (1)	$U_{dec,max}$	%	< 25
Frequency restoration of nominal (+) • step load increase • in less than 60 % of each load sequence interval (time interval)	f_{ri} t_{fri}	% %	± 2 < 0.6 $t_{load\ int\ (+)}$
Frequency restoration of nominal (-) • step load decrease • in less than 80 % of each load sequence interval for disconnection of single largest load (time interval)	f_{rd} t_{frd}	% %	± 2 < 0.8 $t_{load\ int\ (-)}$
Voltage restoration of nominal • step load increase and decrease • within 60 % of each load sequence interval (time interval)	U_r t_{urd}	% %	± 10 ≤ 0.6 $t_{load\ int}$
Speed increase (max) • during recovery from transients caused by disconnection of single largest load	n_{max}	min^{-1}	≤ n_N + 0.75 ($n_{d,0} - n_N$) or ≤ 1.15 n_N (lower value counts)
Speed increase (max) • transient following complete loss of load	n_{max}	min^{-1}	< $n_{d,0}$
(1) Larger decrease in voltage and frequency may be justified for the EDG that carries only one large connected load. Notes: • Acceptance values of frequency and voltage should be based on plant specific analysis, where conservative values of both are measured to prevent load interruption. • A greater percentage of the load sequence interval may be used if it can be justified by analysis. • The load sequence intervals should include sufficient margin for the accuracy and repeatability of the load sequence timer.			

5.4.3 Continuous load rating and safety margins

According to IEEE 387, the continuous load rating is the electric power output capability (kWe) that the EDG can maintain in the service environment for 8760 hours of operation per year with only scheduled outages for maintenance. NRC RG 1.9 also specifies that when the characteristics of required EDG loads are not known accurately (i.e. during an early stage of design), each EDG selected for an on-site power supply system should have a continuous load rating that is equal to the sum of the conservatively estimated connected loads (nameplate rating) that the EDG would power at any one time including a safety margin of 10 to 15 %. However, during the later stages of design (i.e. operating license or combined license stages of review), when the characteristic of EDG loads are calculated and the load profile is specified accurately, the maximum design-basis loads should be within the continuous load rating of the EDG with sufficient margin, for example not less than 5 %. [28, 64]

Based on KTA 3702 standard, the safety margin shall be added to the maximum power load determined from the power balances. In the early design stage (i.e. at the start of the construction of the EDG facility), the safety margin shall be equal to at least 10%. [17]

5.4.4 Overload (short-time load) rating

Based on IEEE 387, the overload (short-time load) rating indicates the electric power output capability (kWe) that the EDG can maintain in the service environment for 2 hours in any 24 hour period, without exceeding the manufacturer's design limits and without reducing the intervals of maintenance established for the continuous load rating. However, the operation at this higher rating does not limit the use of the EDG unit at its continuous load rating. The overloading features of the engine including also KTA 3702 criteria are discussed in Section 6.2.4. [28]

5.4.5 Low-load and idling (no-load) operation

According to IEEE 387, the EDG shall have capability to accept design load following operation at low-load or idling (no-load) for the time required by the equipment specification (the manufacturer specification). Unless time and load parameters for the low-load and idling operation are established by tests and documentation, the following safety measures must be taken into account: [28]

- When 4 hours operation at 30 % or less of the continuous load rating have been accumulated, the EDG shall be operated at least at 50 % of the continuous load rating for a minimum of 30 minutes.
- Operating at 30 % or greater of the continuous load rating shall be limited to the manufacturer's recommendations.

The low-load and idling features of the engine are discussed in Section 6.2.5.

5.4.6 Vibration during operation

As specified in KTA 3702, during continuous and steady state operation vibrations transmitted from the EDG to the civil structure (EDG building) and from the engine to the generator must be limited with the rotational speed adjustment range (see Table 8 in Section 5.4.1). These vibrational forces transmitted from the EDG to the civil structure shall not exceed 3 % of the static loading forces, and the vibrations transmitted from the engine to the generator shall not exceed the vibrational fatigue resistance of the generator. The engine and the generator manufacturers shall have an agreement regarding the generator design or additional measures regarding vibration isolation. Based on IEEE 387, vibration amplitudes caused by the EDG operation must be limited to be within the design capabilities of the EDG and related auxiliary components. In example, components such as solenoids, relays and other auxiliary devices such as pumps etc. shall be mounted in such a way that it minimizes vibration effects of the entire EDG set. [17, 28]

According to KTA 3702, the torsional vibration analysis must be performed for the torsional vibration system of the engine, coupling and generator to demonstrate that the range of vibration will not include any critical values. Also spark failures of the engine cylinders shall be taken into account. Based on IEEE 387, harmful stresses caused by the EDG's torsional vibration shall not occur within a range from ± 10 % of the rated idling speed and ± 5 % of the rated synchronous speed. [17, 28]

6 ANALYSIS OF SELECTED COMPONENTS AND SYSTEMS

6.1 Overview

The objective of this chapter is to analyze certain specific features and requirements of selected EDG components and systems, which are the engine and the fuel oil system. These particular equipment are chosen for deeper analysis because they possess safety related significance and important roles when considering required capabilities and performance for the entire EDG system.

Discussed topics related to the engine consists of the following; overall design and suitability for the nuclear service, stand-by mode and start-up facilitation, overspeeding condition, overload (short-time load) power capacity, low-load (light-load) and idling (no-load) operation, and power adjustment (de-rating) considerations. The fuel oil system associated topics consist of the following; light fuel oil (LFO) characteristics, fuel oil storage and supply, fuel oil filtering and piping, fuel oil cooling (optional), and ambient conditions affecting to fuel oil system.

6.2 Engine

6.2.1 Overall design and suitability for nuclear service

Generally, the engine that is intended to use in nuclear applications such as the EDGs shall be "well proven design". This means that the engine shall not include any new design features, which cannot be verified being adequately reliable and inherently functional for operating in nuclear service environment. The engine manufacturer must provide evidence that the engine type has only minimum design changes in its manufacturing history and the particular engine type has a number of references from the nuclear applications including successful operating history with NPPs. If this latter criterion of references cannot be verified (i.e. due to lack of operating history in nuclear service), the manufacturer shall show that the engine design and type have a required number of references from the industrial power generation field (e.g. the base load and peak load diesel generators with sufficient amount of operating hours, and reliable and successful operating history). [17]

According to KTA 3702, the engine suitability for nuclear service can be demonstrated by a certified satisfactory service life and by type testing. The engine can be assumed to be suitable, if its satisfactory service life is demonstrated by 15 identically designed diesel engines with a total of 7500 operating hours. From these, two of the engines shall account for at least 2000 operating hours each. In addition, the engine shall be type tested successfully in a test run, which is over approximately 100 hours at corresponding rated continuous cylinder output (nominal power). The type test shall be performed in the presence of an authorized audit expert (for example Bureau Veritas) that conducts testing surveillance and grants approval if the type test is successful. Testing programs based on IEEE 387 as well other methods and processes of the EDG qualification for the nuclear service are described in Chapter 7. [17]

6.2.2 Stand-by mode and start-up facilitation

During normal service while the EDG is in the stand-by mode, starting capability and immediate loading of the engine is ensured by maintaining certain engine process parameters (e.g. LO pressure, cooling water temperature) within acceptable limits continuously. This start-up facilitation of the engine is performed by means of pre-heating and pre-lubrication systems as well as other necessary auxiliary systems that are active during the stand-by mode. According to KTA 3702, the following functions with measuring and monitoring shall be active during the stand-by mode in order to facilitate the fast start-up and loading of the engine: [17, 35]

- Lubricating oil and cooling water pre-heating up to specified minimum values;
- Automatic temperature control of cooling water;
- Steady warm-up by means of a cooling water circulation pump;
- Conditions of working pressure for the regulators necessary during run-up procedure;
- Pre-lubrication with devices that cannot cause any damage from excessive lubrication.

The stand-by pre-heated condition for the Wärtsilä 32 EDG engine is defined as follows: [35]

- HT-water (jacket water) temperature is minimum at + 70 °C;
- Lubricating oil temperature is minimum at + 40 °C.

Proper facilitation enables that temperature gradients inside the engine are minimized such that equilibrium state will be attained faster in the start-up and subsequent loading phases. This ensures that the start-up time is minimized and start-up reliability is higher. IEEE 387 standard defines that the equilibrium temperature of the engine is the condition at which the engine jacket water (HT-water) and lubricating oil temperatures are both within ± 5.5 °C of their nominal operating values, which are established by the manufacturer. Typically the steady-state temperature and full load condition is achieved approximately within 60 seconds after the start-up if the loading is successfully completed. In addition, IEEE 387 requires that the engine shall be capable of starting, accelerating and being loaded with the design load within the time required by the equipment specification as follows: [28, 67]

- From the normal stand-by condition;
- With no cooling available, for a time equivalent to that required time to bring the cooling equipment into service with energy from the EDG unit;
- On a restart with an initial engine temperature equal to the continuous rating full-load engine temperature.

6.2.3 Overspeeding condition

The engine overspeed is one of the undesired conditions that allow shutdown of the engine safely even if it is operating in the emergency mode. Mechanically the engine is set to operate in a specified speed range (i.e. 750 rpm with proper speed tolerance band) in order to maintain the EDG’s generator electric output power in correct frequency. The engine speed is controlled by the engine speed and load controller and the governor, which regulates fuel injection to the cylinders (fuel rack control). For example, if the engine governor fails to maintain the engine speed or there is a failure in the fuel injection system, the speed can increase to an unsafe level, which is called overspeeding condition. This overspeeding could result in severe engine and/or generator damage and fire hazards causing possible danger to operating personnel as well. In addition, the overpeed can result due to an improperly adjusted control system or when the EDG supplied emergency loads are suddenly lost (large load rejection) for some reason. [60, 64]

To prevent the engine speed for increasing too much, the engine requires an overspeed trip device and a redundant speed monitoring. The overspeed trip device can be a separate governor driven by the engine gear train, or it may be a separate overspeed trip mechanism. The Wärtsilä 32 EDG engine is equipped with an electro-pneumatic overspeed trip device with mechanical back-up system (optional), which both works independently from each other and from the speed governing system. Normally the mechanical overspeed trip or governor driven trip is required to be reset manually. The overspeed prevention is active under all operating modes of the EDG. Table 11 below shows the overspeed trip limits according to KTA 3702 and IEEE 387 with NRC RG 1.9. [35, 60]

Table 11: Engine overspeed tripping limits based on KTA 3702 and IEEE 387 with NRC RG 1.9. [17, 28, 64]

Engine overspeed tripping limits			
Standard and definitions	**Symbol**	**Unit**	**Value**
KTA 3702 • % of nominal speed	$n_{d,0}$	%	≤ 120
IEEE 387 (NRC RG 1.9 included) • % of nominal speed	$n_{d,0}$	%	110 – 115 (typically) or 75 of difference between nominal speed and overspeed trip set point, whichever is lower

6.2.4 Overload (short-time load) power capacity

The overload (short-time load) power capacity of the engine indicates that extra power output capability that it can maintain for a specified time period without causing any harm or damage especially to the engine itself, or to the generator, or to other components and auxiliary systems connected to the EDG system. For example, the coupling between the engine and generator shall be also designed to withstand the overloading conditions. [17, 28, 60]

The engine shall be overloaded first time according to the engine manufacturer's design limits before the nuclear service (e.g. in the pre-operational testing). As an example, such conditions where the engine overload may occur during the service in emergency operation with the NPP are if power demand of the EDG supplied loads is more than expected (e.g. too heavy loads are applied), or the loading sequence does not comply with the engine output capability. Also parallel operation with the off-site grid, or synchronization with other EDG's can result too excessive frequency transients, which may force the individual EDG engine to be overloaded. Table 12 below shows overload power capacity limits for the engine based on IEEE 387 and KTA 3702. [17, 28, 60]

Table 12: Engine overload power capacity limits based on KTA 3702 and IEEE 387. [17, 28]

Engine overload power capacity limits				
Standard and definitions	**Symbol**	**Unit**	**Value**	**Duration**
IEEE 387 • % of nominal load	P_{ol}	%	105 – 110	2h for every 24 h
KTA 3702 • % of rated load	P_{ol}	%	≥ 110	1h for every 12h
Notes from KTA 3702: • engine overload shall be sufficient to comply with dynamic tolerances under consideration of load steps and load acceptance times • overload power capacity may not be used to meet static power criteria during emergency operation (however it shall be provided for 1 h period for performance certification and testing • quantity of injected fuel shall be limited such that specified overload capacity cannot be exceeded				

6.2.5 Low-load (light-load) and idling (no-load) operation

The low-load (light-load) operation of the engine results when the EDG supplied loads are reduced such that the engine power output is significantly lower than the continuous rated power output. According to IEEE 387, the low-load limit value is under 30 % of the rated continuous load. The engine idling (no-load) operation corresponds the situation when the engine is running without load. Usually the allowable durations and power limits of low-load and idling operation are defined by the engine manufacturer. The requirements and considerations based on IEEE 387 for the idling and low-load operation of the engine are summarized in Table 13 below. [28]

Sometimes the customer may require even longer period of time for the engine idling and low-load operation capability. Regarding to this, the engine operation with low-load or idling conditions is not recommended very often. Periodically occurring low-load or idling operation can cause the engine fuel injection equipment (i.e. fuel injection pump and injection valve nozzle) to wear more quickly. Therefore, special attention should be paid for the monitoring and maintenance, and possibly replacing these components may take place more frequently than usually. One important concern also is soot build-up in the turbocharger, and the exhaust gas system in general. Prolonged low-load or no-load operation of the engine can lead to accumulation of unburnt fuel (soot) into the exhaust gas system, which in turn may result into explosion in the exhaust gas ducting. [12, 68, 69]

Table 13: Allowable low-load and idling operation values with related durations according to IEEE 387. [28]

Engine low-load (light-load) and idling (no-load) operation limits (acc. IEEE 387)
• Light-load or no-load capability shall be demonstrated by load capability test, wherein light-load or no-load operation shall be followed by a load application of at least 50 % of the continuous power rating (kW) for a minimum of 0.5 h. • Unit shall be capable of accepting design load following operation at light-load or no-load for the time required by the equipment specification. • If time and load parameters for light-load and no-load operation are not established by tests and documentation, the following precautions shall be taken into account: a) When 4 h operation at 30 % or less of the continuous load rating have been accumulated, the engine unit shall be operated at a load of at least 50 % of the continuous load rating for a minimum of 0.5 h. b) Operating at 30 % or greater of the continuous load rating shall be limited to the manufacturer’s recommendations.

6.2.6 Power adjustment (de-rating) considerations

The EDG engine is designed to operate at its rated continuous power output to meet specified site conditions (ambient conditions), which often are assumed to be the most extreme conditions that may occur at the NPP site. This means that the EDG engine is always adequately oversized (i.e. added safety margin to the design load rating) to fulfill requirements that extreme ambient conditions may posit to the engine power output. [15, 28]

The main reason why the normal engine power adjustment methods during operation shall not be applied to the EDG engine is that the EDG must perform its predefined safety functions in all conditions and whenever required. Therefore the EDG engine is not equipped with any automation and monitoring devices, which enables the power adjustment functions that may cause interferences and degrade in worst case the engine power output during actual demand in the emergency operation. However, the power output of the EDG engine can be de-rated manually by the operator when the EDG is tested and in cases when the unit will not operate in real nuclear service operation. [68]

6.3 Fuel oil system

6.3.1 Light fuel oil (LFO) characteristics

Light fuel oil (LFO) is a product from distillation process and exists in several different grades from pure distillate to different grades mixed with heavy fuel oil (HFO). The Wärtsilä 32 EDG engine is operated only with high-quality LFO for fulfilling reliability requirements. Other liquid fuel oil blends used in conventional diesel engine power plants such as heavy fuel oil (HFO) or liquid biofuel (BFL) are not discussed in this study.

LFO used in the engine shall not contain any water or solid particles, and it must be properly cleaned from substances or chemical waste, which may affect directly to the performance of the engine. These harmful substances in LFO can cause irregularities in the combustion process in the cylinders, and may cause wear and tear to the components. Typical characteristics and quality limits of LFO are specified for example in ISO 8217:2012(E) standard, which are summarized in Table 14 below. ASTM D-975 standard can also be used for this purpose. [6, 29, 35, 70]

Table 14: Main characteristics of LFO according to ISO 8217:2012(E). [6, 29, 35, 70]

Light fuel oil (LFO) main characteristics (acc. ISO 8217:2012(E))		
Parameter	**Quality limit**	**Unit**
Viscosity	min. 1.5 / max. 11 typical value for arctic grade LFO: 1.5 – 3	cSt at 40 °C
Injection viscosity	min. 2.0 / max. 24	cSt
Density	min. 855 / max. 900	kg/m^3 at 15 °C
Water	max. 0.3	vol-%
Sulphur	max. 2.0	mass-%
Ash	max. 0.01	mass-%
Flash point	min. 60	°C
Pour point	max. 6	°C

Additional quality properties for LFO used in the engine are defined case by case to meet project specific requirements. Often these additional requirements regarding to fuel oil are dependent on ambient conditions specific for the NPP site. As an example, winter quality (arctic grade) LFO should be used, if there is a risk that ambient temperature may drop below 0 °C. Summer quality LFO can be considered, if EDGs are located at the site where ambient temperature won't fall below 0 °C in any case. In very hot ambient conditions, it should be taken account that high temperatures decrease fuel oil viscosity, which instead may cause leakage and injection problems to the cylinders as well as to the fuel oil pumps and piping. Therefore, low viscosity fuel oil injection pumps and a LFO cooler can be considered for ensuring proper fuel injection. [68]

6.3.2 Fuel oil storage and supply

According to KTA 3702 standard, the fuel oil that the engine consumes (LFO) shall be stored in an individual storage tank for each train of the EDG, from which it's pumped to the corresponding day tank (operating tank). A leakage indicator shall be installed in case of a double-walled fuel oil tank or of a single-walled fuel oil tank with collecting sump. It shall be possible to drain the water from the lowest point of each tank by suction from the top. Fuel oil extraction pipe lines shall be installed at a sufficient height above the tank base. In case the fuel oil surface level in the storage tank falls below the minimum value, an alarm shall be initiated. [17]

The sizing of the storage tank is normally done based on continuous operation duration of the EDG. Table 15 below shows specific values of the continuous operation durations required for the fuel oil supply from the storage tank without refilling based on applicable standards.

Table 15: Fuel oil storage tank capacity according to relevant standards. [17, 71, 72]

Standard	**Storage tank capacity (minimum duration) (based on continuous operation of the EDG)**
KTA 3702 (German)	72 hours (3 days)
RD 0052-00 (Russian)	120 hours (5 days)
ASME/ANSI-59.51 (U.S.)	168 hours (7 days)

Each individual EDG shall also be equipped with an individual fuel oil day tank (operating tank), wherein the surface level of fuel oil shall be monitored. If this surface level drops below the minimum value, an alarm shall be initiated. The day tank shall be located such that it is elevated at a necessary height above the engine to ensure positive suction for the engine driven fuel oil feed pump. In addition, a return overflow from the day tank to the storage tank shall be provided. Table 16 below presents specific values of the continuous operation durations required for the fuel oil supply from the day tank to the engine based on relevant standards. [17]

Table 16: Fuel oil day tank capacity according to relevant standards. [17, 71, 72]

Standard	**Day tank capacity (minimum duration) (based on continuous operation of the EDG)**
ASME/ANSI-59.51 (U.S.)	1 hour
KTA 3702 (German)	2 hours
RD 0052-00 (Russian)	5 hours

6.3.3 Fuel oil filtering and piping

The fuel oil filters shall be installed between the day tank and the engine, and between the storage tank and the day tank. The filters shall be duplex filters, and cleaning of them shall be possible to perform during normal operation of the EDG. [17]

The internal fuel oil system shall be equipped high-pressure fuel oil pipelines with double walled design or provided with an equivalent shielding. This shall prevent fuel oil leakages from coming into contact with components having high surface temperatures (above 200 °C) inside the engine. As an example, if an inner fuel oil pipeline breaks, an outer wall of pipeline prevents fuel oil leaking to surroundings and hot surfaces. In addition, the internal fuel oil system piping shall have falling gradient such that positive net suction is guaranteed for the engine. [17]

6.3.4 Fuel oil cooling (optional)

The fuel oil cooling is an alternative configuration added to the EDG's fuel oil system, where LFO is cooled after it's has been passed through the engine circulation. LFO temperature tends to rise during the engine operation, and this may cause problems such as too low fuel viscosity, which instead can cause possible fuel leakages and injection problems. Also fuel oil cooling maintains LFO temperature below flash point. The fuel oil cooler allows LFO viscosity to be brought to an optimum value before LFO is returned back to the day tank. LFO can be cooled by the LT-water heat exchanger, sea water heat exchanger, radiators or chiller, or by combination of these (redundant solution). The cooler is typically located in the return fuel pipeline from the engine to the day tank. The selected method of the fuel oil cooling depends strongly on ambient conditions and desired fuel oil viscosity. [45, 68]

Typically LFO is cooled by a plate type heat exchanger that is utilizing cooling water system's LT-water or raw water as a cooling media at its cold side. A wax-type thermostatic three-way valve regulates water temperature downstream from the plate heat exchangers. As default in normal situation, the heat exchanger is bypassed. Since the water temperature at the outlet of the valve reach the opening set point, the valve will start opening and admits LFO to flow through plate heat exchanger. If this main heat exchanger (LT-water or sea water cooler) fails to cool LFO for some reason, a redundant plate heat exchanger will take over. This redundant heat exchanger utilizes water from a secondary cooling circuit (radiator circuit) as a cooling media at its cold side. Also in this arrangement, a wax type thermostatic three-way valve regulates water temperature downstream from the plate heat exchangers, and as default the redundant heat exchanger is bypassed normally. Figure 34 below shows a principled fuel oil system flow diagram of the EDG system having a heat exchanger (LT-water) and sea water cooler as a fuel oil cooling method. [45, 68]

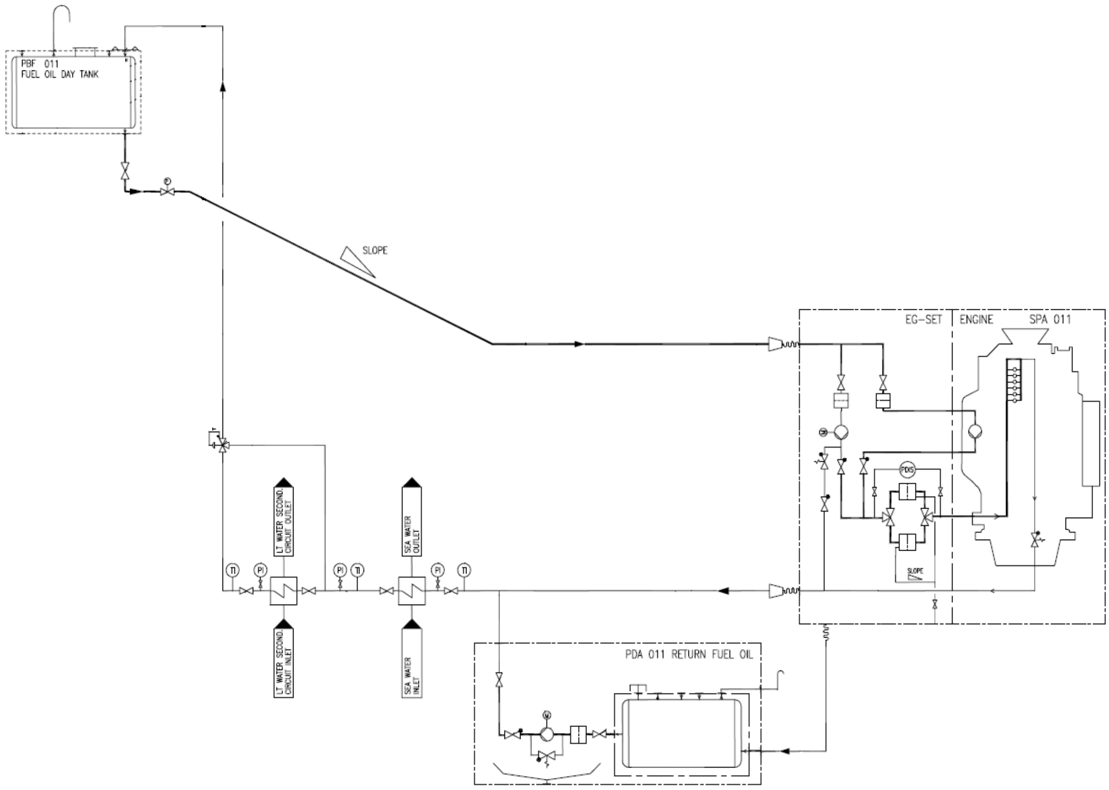

Figure 34: Principled fuel oil system flow diagram of the EDG system with a heat exchanger and a sea water cooler as a fuel oil cooling method. [45]

The fuel oil cooling with radiators is a closed circuit system, where LFO flows through a finned tube coil that is cooled by a forced air flow inside the radiators. A radiator fan is controlled by the EDG’s control system. The temperature control is done by temperature sensor installed in the fuel oil return line from the engine, right after the thermostatic three-way valve. As an example, the radiator fan starts cooling when LFO temperature reaches 40 °C and stops when LFO temperature drops at 30 °C or below. [45, 68]

The chillers are designed to work within a certain temperature range. The fuel oil cooling can be done by one circuit or two circuits chilling. A compressor chilling is using heat pump principle to utilize a condensation heat (heating) and an evaporation heat absorption (cooling). In condensation, a cooling media turns from gas to liquid phase, and in this process heat is rejected. In evaporation, cooling media turns from liquid to gas phase, and in this process heat is absorbed meaning that cooling is produced. [45, 68]

6.3.5 Ambient conditions affecting to fuel oil system

Typically the fuel oil storage tank is placed outside from the EDG building. If ambient conditions are extremely cold, there is a risk that LFO may reach its wax point or filter plugging point or pour point. To avoid this risk, the storage tank can be insulated or it can be placed underground. Additionally, the fuel oil flow can be warmed appropriately by trace heating inside fuel oil lines, and/or fuel oil can be circulated via day tank. [45, 68]

Hot ambient conditions are linked to the cooling water system's performance, and therefore it affects also to fuel oil cooling arrangements. As mentioned earlier, LFO needs to be cooled in order to avoid too low viscosity, and very hot ambient conditions typically strengthen this effect further. A low viscosity of LFO can cause fuel injection problems into cylinders, which may lead to the engine starting problems, leakages from pumps and pipelines as well as injection problems into the cylinders. In case the engine type specific minimum viscosity (2 cSt) can't be met, low injection fuel oil pumps can be considered, which are able to pump LFO with lower viscosity. [45]

7 EDG QUALIFICATION AND OTHER CONSIDERATIONS

7.1 Overview

The purpose of the qualification (or validation) is to demonstrate and verify in various ways that design, performance, reliability and other features of the EDG system have achieved an appropriate level of quality for the actual nuclear service with the NPP. The requirements to be reached by means of the qualification are normally set by the legislation and applicable standardization, but also the customer (NPP operator) and the EDG manufacturer (e.g. Wärtsilä) typically have their own specific criteria and demands, which are included to the qualification process.

After successful qualification, the EDG system is qualified and will be capable for operation with the NPP throughout its qualified design service lifetime (typically 40 – 60 years). Wärtsilä has developed its own qualification procedures in conformance with relevant international and national regulations and standards. The complete qualification process can be divided into the following main procedures based on methods applied by Wärtsilä:

- Safety grading (safety classification);
- Technical performance qualification (analysis and testing);
- Environmental qualification (ageing and seismic).

In this chapter, most attention has been given to the safety grading and technical performance qualification procedures whereas the environmental qualification is explained only at the general level. Also at the end of this chapter other EDG related aspects are provided consisting of following topics; site specific ambient conditions, reliability and failures, and design service life.

7.2 Safety grading (safety classification)

The safety grading (safety classification) is typically the first step of the EDG qualification process. It allows categorizing components and sub-systems of the EDG system (i.e. crankshaft, storage tank, cooling system, lubricating oil system etc.) into different categories. The main goal is to find out safety critical components and systems, which have relevancy of impact on the safe and reliable operation of the EDG system. Properly executed safety classification enables the achievement of the desired level of nuclear safety for each component and yet for the entire EDG system during every phase of design, procurement, manufacturing, assembly and commissioning. [73]

According to the IAEA Safety Series No. 50-C/SG-Q standard, a graded approach shall be used for defining the safety criticality of the EDG system components and related systems. As mentioned, the safety grading results a component categorization list, which is established at the start of the EDG project and is typically also used as a pattern for complete project execution. The safety grading takes account specific requirements of the project, adjoining systems and classifications as well as relevant codes and standards. Both domains of the EDG system design, mechanical and electrical, are addressed to functional and structural safety categories by the complete safety grading procedure. [21, 74]

7.2.1 Failure mode, effects and criticality analysis (FMECA)

One important tool that Wärtsilä utilizes to the safety grading for nuclear applications is FMECA (Failure mode, effects and criticality analysis). The safety grading can be done also by other tools such as operational experience, which is based on historical data collected from the field, or by probabilistic analysis/assessment (PRA). [22, 73]

FMECA is an extension to FMEA (Failure mode and effects analysis) that is a risk assessment method for analyzing and identifying potential failure modes, their causes and effects on the performance of the overall system (i.e. any applicable technical system). The probability of occurrence, probability of detection and severity of a failure are assessed in FMEA. In addition to this, FMECA gives means for ranking severity of failure modes, which allows prioritization of countermeasures. Both analysis methods, FMEA and FMECA, are based on IEC 60812 standard. [75]

FMECA results that some components are safety critical (safety related, SR) and some others are not (non-safety related, NSR). FMECA combines factors as severity, probability of occurrence and probability of detection to produce a metric called criticality. All factors (severity, probability of occurrence and detection) have ranking from 1 to 3. [22, 73, 75]

7.2.2 Wärtsilä Component Categories (WCCs)

Wärtsilä Nuclear Safety Grading Procedure produces a component categorization, which consists of three levels of safety significance called as Wärtsilä Component Categories (WCCs). Criticality values of each component or system from FMECA evaluation is directly linked to WCCs. A high criticality will lead to a safety related classification (WCC1 and WCC2) and a low criticality will lead to a non-safety related classification (WCC3). [21, 73]

WCC1 components or systems have high safety significance meaning that a single failure of a component or a system prevents entirely the safe operation of the EDG system. Generally, all main components of the engine are classified into WCC1. For example, if the engine crankshaft breaks down during operation, it will lead to an immediate shut down of the engine and can also severely damage other equipment of the EDG. Therefore the EDG system is not able to fulfill its safety-related functions if WCC1 component fails for some reason. [73]

Components or systems classified into WCC2 have moderate safety significance meaning that a single failure of a component or a system prevents only partially or does not solely prevent the safe operation of the EDG system. It still can perform its safety related functions for a certain period of time, but failure cause needs to be identified and fixed as soon as possible, or component replacement can be done during next maintenance period. [73]

WCC3 components or systems have no relevant safety significance, thus a single failure of a component or a system does not prevent the safe operation of the EDG system. This means that the EDG system can perform its safety related functions without any instant repairing or replacement actions. [73]

7.2.3 Safety grading approaches and correspondences

For the engine components, the safety grading can be carried out through two different approaches depending on the standardization defined by the customer and the national authorities. Typically FMECA analysis is done, when the engine design is based on IEEE 387 standard. As described, FMECA analysis produces classifications for safety-related and non-safety related components, which are linked into corresponding WCCs. [22, 73]

When the engine design is done in accordance with KTA 3702 standard, that particular standard defines the list of main components, which are considered to be WCC1 components. Other components in KTA 3702 standard are counted as industrial grade components, which equals WCC3 normally. However, often the customer specifies additional requirements, which needs to be applied into the design of the engine. As an example, the customer may demand that WCC3 component is lifted up to WCC1 due to its safety related purpose. For the auxiliary systems, FMECA analysis is applied typically. [22, 73]

The correspondence between WCCs determined by Wärtsilä and the safety classes defined by national authorities or international organizations will always be done project specifically. Table 17 below shows examples of correspondences between WCCs and nuclear safety classifications from various different regulatory origins.

Table 17: Correspondences between WCCs and national or international nuclear safety classifications (boundaries between different classes are only indicative). [21]

Wärtsilä Component Category	WCC1	WCC2	WCC3	
National or International standard	**Classification**			
IAEA	Systems Important to Safety		Systems not important to safety	
	Safety system	Safety related system		
IEC	Category A	Category B	Category C	Unclassified
RCC (France)	1E	2E	IFC/NC	
European Utilities Requirements (EUR)	F1A (Automatic)	F1B (Automatic and Manual)	F2	Not Classified
NORMS (UK)	Category 1	Category 2		Not classified
IEEE (USA)	1E		Non-nuclear safety	
YVL (Finland)	2	3	EYT	
KEPIC (South Korea)	Q Class	A Class	S Class	
KTA (Germany)	Components table 5.1 (KTA 3702)	Other components		
GOST NP (Russia)	2O	3	4	

According to Finnish YVL –Guides the EDG system as a whole is classified in the safety class 2. However, as mentioned in the previous chapter, some components of the engine are industrial grade components (i.e. bolts and nuts), which do not have any nuclear safety relation. This leads to an interpretation that these components are typically classified into EYT class, which is corresponding WCC3. Safety class 2 equals WCC1 and WCC2 corresponds safety class 3 in the YVL –Guides. Safety related (SR) components defined in IEEE 387 standard are defined as Class 1E components. Non-safety related (NSR) components are defined being as non-nuclear safety (Non-Class 1E) components. [15, 21, 28]

7.3 Technical performance qualification by analysis

The purpose of the entire technical performance qualification process is to provide assurance that nuclear applications meet their technical performance requirements. Performance related criteria are defined by the applicable regulatory guides, codes and standards as well as by the technical specifications received from the customer. Typically technical performance aspects considered for the EDG system consist of at least power output, loading sequence, voltage drop, auxiliary systems, control logics and protection systems etc. The qualification process of technical performance can be divided into two parts; analysis and testing.

The qualification by analysis is normally conducted inside the design process. Final outcome of this process consists of for example several technical drawings, technical specifications, modelling calculations and notes etc., which are used as a part of the project execution. Detailed design is reviewed against basic design and design specifications before releasing the product for manufacturing and testing. As applicable parts, the design review is performed with the customer and possible deviations are checked that the whole design of the application meets the requirements set up for the project. After this follows the verification phase where the product design is verified and justified by Wärtsilä. This includes i.e. compliance with technical specifications (acceptance criteria), calculation notes and validity of design software. [21]

7.4 Technical performance qualification by testing

The testing is a very important part of the qualification process. In order for the EDG to be used as an on-site emergency stand-by power source in the NPP, the unit must first be type qualified for the nuclear service by passing successfully several challenging and rigorous performance tests runs and analyses. The performance testing demonstrates that the EDG has a required capability to perform its intended functions under monitored testing conditions. Both standards, KTA 3702 and IEEE 387, include detailed requirements how the EDG system shall be tested, and typically these are clarified verified by the engine and generator manufacturers in compliance with certified surveillance and inspection facet (e.g. Bureau Veritas). Usually the EDG manufacturer or assembler has its own testing facility or laboratory for conducting the first parts of testing. [28, 76]

The upcoming descriptions of the qualification by testing are based on IEEE 387 definitions and requirements. KTA 3702 testing procedures are not discussed in this study. The main parts of the performance testing based on IEEE 387 can be divided as following list shows. Detailed content of each testing program are presented in Appendix A.

- Factory production/acceptance testing (FAT);
- Type testing;
- Site testing.

7.4.1 Factory production/acceptance testing (FAT) (IEEE 387)

The factory production testing (factory acceptance testing, FAT) shall be performed in accordance with a written test plan. Usually FAT is conducted in a factory or facility of the manufacturer or assembler, but FAT tests may also be performed at the NPP site location after delivery. Related documentation shall encompass for example the EDG equipment performance specifications, identification of specific feature or features to be demonstrated by the test, the test plan and the report of the test results. FAT testing may be supplemented or substituted by analyses in those cases where testing is not practical, but the same criteria for the EDG performance placed in IEEE 387 standard shall be demonstrated. FAT testing program consist of the engine tests, generator tests, and the tests of the excitation and control as well as other accessories/auxiliaries of the EDG system. [28, 76]

7.4.2 Type testing (IEEE 387)

The EDGs that are not previously type tested for the nuclear service with the NPP shall be subject to a type testing program that consists of the load capability, start and load acceptance, and margin tests. These tests typically are performed at the factory or testing facility of the manufacturer or assembler, but it is allowed to conduct the type tests at the NPP site if measuring conditions are equivalent compared to the factory testing conditions. The type testing may be conducted on single or multiple units, and the qualification of one unit will qualify same type of units for equal or less severe service. If the start and load acceptance tests are performed using more than one identical unit, then each of these identical units must be included to the load capability and margin tests. Normally the type tests are executed following the successful completion of the FAT testing, but in some cases these can be done also in reverse order. [28, 76]

The scope of the type tested equipment of the EDG system is specified in both, IEEE 387 and KTA 3702, standards (see figures 7 and 8 in Section 3.3.1). Any changes in the type tested equipment may lead to a new type test.

Load capability tests
The purpose of the load capability tests is to demonstrate that the EDG has a capability to carry the defined rated loads at rated power factor (PF) for the time period specified, and to successfully reject load. One successful completion of this test sequence is enough to satisfy the criteria for the load capability. [28, 76]

Start and load acceptance tests
The target of these tests is to verify that the EDG is capable of starting and accepting load within the period of time necessary to fulfil the plant design requirement. [28, 76]

Margin tests
The margin tests demonstrates the capability of the EDG to start and carry loads that are greater than the magnitude of the most severe step load within the plant design load profile, including load step changes above base load. The limiting case step change over base load as defined by the design load profile shall be demonstrated. This step change is not necessarily the largest step change, but may be a smaller step change as the full-load capability of the EDG is approached. It is possible to combine the margin tests with the load capability tests or start and load acceptance tests. At least two margin tests shall be performed using either the same or different load arrangement. [28, 76]

7.4.3 Site testing (IEEE 387)

The site testing program consists of the site acceptance tests (SAT), pre-operational tests and periodic tests. This series of tests are always conducted by the NPP operator and in that specific location where the EDGs are placed for the nuclear service at the NPP site. [28, 76]

Site acceptance tests (SAT)
These tests are performed after final assembly and preliminary start-up testing such that each EDG is tested to demonstrate that they are capable of perform their intended functions as required. SAT testing consists of several sub-tests; starting test, load acceptance test, rated load test, load rejection test, electrical test and sub-system test. [28, 76]

Pre-operational tests
The pre-operational testing is carried out after completion of SAT. The aim is to demonstrate starting and operational adequacy of the EDG. The pre-operational tests should be preceded by a time period with pre-lubrication of the engine and should be in general accordance with the recommendations of the manufacturer for reducing engine wear. This also includes sufficient cooling down operation at reduced power load followed by lubrication after operation. Typically these tests are performed at a power factor (PF) as close as it is practical to the design load PF so that the voltage conditions of the NPP are acceptable. Similarly like SAT, the pre-operational tests consist of various sub-tests; reliability test, loss-of-offsite power (LOOP) test, safety injection actuation signal (SIAS) test, combined SIAS and LOOP test, largest-load rejection test, design load rejection test, endurance and load test, hot restart test, synchronizing test, protective-trip bypass test, test mode override test and independence test. [28, 76]

Periodic tests
After installed for the service, the EDG shall be tested periodically to demonstrate that the continued capability and availability to perform its intended functions is acceptable. Some tests belonging to the periodic testing may be combined and not necessarily performed individually. Also it is not necessary to begin these periodical tests from the EDG's stand-by conditions unless it is otherwise specified. The periodic testing consists of the availability tests, system operation tests and independence tests. [28, 76]

The aim of the availability tests is to demonstrate the continued capability of the EDG to start and accept load. Each unit are started and loaded at least once in 31 days (slow-start and load-run test). In addition, the availability shall be demonstrated by conducting a fast-start and load-run tests once every 6 months. The system operation tests demonstrate the ability of the EDG to perform its intended functions under simulated accident conditions. These tests are executed during shutdown/refueling outages of the NPP once every 2 years. The system operation tests consist of several sub-tests; combined SIAS and LOOP test, largest-load rejection test, design-load rejection test, endurance and load test, hot restart test, synchronizing test, protective-trip bypass test, and test mode override test. The independence verification test is conducted in the case, where independence of the EDG may have been affected for example due to any modifications, or every

10 years during the NPP shutdown or refueling outage, whichever time interval is shorter. [28, 76]

7.5 Environmental qualification (aging and seismic)

7.5.1 Aging qualification

According to IEEE 323, the main objective of the aging qualification is to demonstrate with reasonable assurance that Class 1E equipment (SR electrical equipment) for which a qualified life or condition has been established can perform its intended safety-related functions before, during, and after applicable design basis events, and without experiencing any failures. Typically, all safety-related equipment of the I&C-system, electrical motors and other electrical equipment are applied to the scope of the aging qualification. In case the equipment has significant aging mechanisms, it shall be subject to pre-aging tests prior to seismic tests. [77, 78]

There are different aging mechanisms originating from varying or constant environmental conditions (normal and abnormal) that may cause degradation to the EDG system's performance over time or age-related failures to certain components during their service life. Types of significant aging mechanisms include for example thermal, wear (i.e. mechanical and electrical cycling), and vibration. Radiation is not typically applicable to the EDGs, since they are located outside of the containment. [28, 77, 78]

7.5.2 Seismic qualification

According to IEEE 344, the purpose of the seismic qualification is to demonstrate that the equipment of the EDG system has ability to perform its safety function during and after the time it is subjected to the forces resulting from one safe shutdown earthquake (SSE). In addition, the EDG equipment must withstand the effects of a number of operating basis earthquake (OBE) before experiencing the SSE. Another applicable standard for the seismic qualification is IEC 60980 where basic principles are similar to IEEE 344. [79, 80]

The seismic qualification is typically required for all SR components of the EDG system. The safety grading works as a basis for determining, which components or systems are categorized into SR or NSR classes. NSR components demand verification by means of analysis or testing to show that failure of these will not reduce the SR functions of the whole EDG system when a seismic event occurs. The functional testing shall be performed after seismic testing in order to assure that the capabilities and performance of the EDG system will be sufficient. The recommended methods for the seismic qualification can be categorized as follows based on IEEE 344: [28, 79]

- Predict the performance of the equipment by analysis;

- Test the equipment under simulated seismic conditions;
- Qualify the equipment by a combination of test and analysis;
- Qualify the equipment through the use of experience data.

The selection of the method should be based on its practicality for the type, size, shape, and complexity of the equipment configuration. The required safety function depends on the equipment itself, and on the system in which it is meant to function. The required safety function during the earthquake and after it is often the same, but it can also be different depending on the case. As an example, a single component may be required to perform no active functions during and after the earthquake, or it only may be required to withstand the earthquake and perform an active function after it, or any combinations of these. Another component may only be required to maintain structural integrity during and after the earthquake. In conformance with the aging qualification based on IEEE 323, it shall be demonstrated that the equipment have the capability to perform its safety function throughout its qualified life including its functional operability during and after the SSE at the end of the qualified life. [77, 79]

7.6 Other EDG related considerations

7.6.1 Site specific conditions (environmental conditions)

Similar to the design basis of the NPP, the EDG system's normal operation and performance can be threatened by possible risks resulting from abnormal ambient conditions (e.g. severe weather) or other environmental conditions that may occur at the NPP site region over the service life time. These site specific conditions are always determined case by case, and influencing factors and possible consequences are typically taken into account in the early phase of the design. Normally, the NPP operator provides initial data of prevailing conditions and expected events (design basis and beyond design basis events). There are several sources of information and research methods that can be utilized for identifying and analyzing probabilities of possibly occurring adverse environmental conditions. For example, climate zone categorizing, long-term forecasts, seismic activity analysis, statistical history data of occurred external events at the NPP region, PRA analysis etc., are commonly used for this purpose.

From the EDG performance point of view, both standards, KTA 3702 and IEEE 387, define requirements that the EDG system shall be designed such that the most unfavorable ambient conditions are taken into account, and so that all operating modes of the EDG can be performed securely and reliably without interruptions under these conditions. For example, special attention should be paid to external auxiliary system components or parts that are located outside having a direct interface with ambient air, and which may be impacted by possible changing weather conditions (e.g. piping, tanks, radiators etc.). However, in all cases the safety-related components of the EDG system come first in ranking, when determining equipment that should be protected more than usual. [17, 28]

Normal ambient conditions

The normal ambient conditions can be divided into two categories; conditions outdoors (outside the EDG building) and conditions indoors (inside the EDG building, inside the EDG/engine room and inside the control/electrical room). Table 18 below shows the main parameters of normal ambient conditions that typically are considered when evaluating required performance of the EDG system. [35]

Table 18: Main parameters of normal ambient conditions (outdoors and indoors) to be taken account in design and performance of the EDG system. [17, 28, 35]

Ambient conditions outdoors (outside EDG building)			
Parameter	**Symbol**	**Unit**	**Remarks**
Air temperature	T_{out}	K °C	• Maximum and minimum temperature • Annual average temperature • Extreme (cold/warm) values measured at site • Season variations (summer/winter) with durations • Dry bulb thermometer temperature
Altitude above sea level (elevation, height)	h	m	• Stationary parameter • Relation between atmospheric or barometric pressure • Mean sea level (MSL)
Atmospheric pressure (barometric pressure)	p	Pa bar mm Hg	• Depends mainly on altitude above sea level • Air temperature and humidity affects to atmospheric pressure
Relative air humidity	Rh	%	• Maximum and minimum value with durations • Prevailing weather conditions at site region • Humidity in summer and winter • Mainly climate zone related
Wind speed	v_{wind}	m/s	• Typical/average wind speed measured at site • Extreme wind speed
Sea or raw water temperature (in case EDG's external cooling system is based on sea/raw water cooling circuit)	T_{sea} T_{raw}	K °C	• Maximum and minimum temperatures • Annual average temperature • Season variations (summer/winter) with durations
Ambient conditions indoors **(inside EDG facility, inside EDG/engine room, inside control/electrical room)**			
EDG/engine room temperature	T_{in}	K °C	• Maximum and minimum value • During EDG operation
Control/electrical room temperature	$T_{in,\ control}$	K °C	• Maximum and minimum value
Relative air humidity indoors	Rh_{in}	%	• Maximum value

Extreme weather, natural phenomena, external hazards

The following list shows examples of some extreme weather conditions, natural phenomena and external hazards that should be recognized. For some events probabilities of occurrences are very low, but in case of these events actually take in place they may cause substantial degradation to the EDG system's performance and compromise its capability to perform its intended safety functions during emergency demand. For further reading related to this topic and how the performance of the EDG system may be influenced by natural phenomena and weather conditions, references [81], [82] and [83] are recommended. [81, 82, 83]

- Extreme temperature variations;
- Earthquake, seismic vibrations;
- Hurricane, tornado, extreme wind speed, strong storm, wind generated missiles;
- Sea level rise, flooding, tsunami;
- Heavy rain, rain precipitation;
- Snowfall, snow precipitation, icing and ice formation;
- Dusty air, sandstorm;
- Volcano ash;
- Meteor impact;
- Lightning, thunderstorm;
- Cooling water intake clogging (if raw/sea water cooling is used) caused by algae, jellyfish, supercooled ice particles beneath water surface;
- Landslide;
- Climate change effects in site specific area;
- Man-made hazards (explosions, fires, airplane crashes etc.).

Electrical disturbances and other interferences

There are also certain electrical disturbances and interferences (for example man-made or generated by the nuclear operating environment by itself) that shall be considered in the design and performance of the EDG system. Typically, the EDG system should have capability to withstand at least to the following conditions: [12, 84]

- Electromagnetic interference (EMI) (electromagnetic compatibility, EMC);
- Electrostatic discharge (ESD);
- High-power electromagnetic pulse (HEMP).

Especially the electrical components and sub-assemblies of the I&C-system shall be designed in conformity with relevant standards regarding to the electromagnetic compatibility (EMC) and emissions of electrical appliances. The effects of electromagnetic interference (EMI) shall be taken into account in the design of the control cabinets and enclosures, and particular attention shall be paid to design of cable glands, grommets, lead-ins and grounding. The generator is not vulnerable to EMI, except for climatic voltage surges (lightning strikes). Basically all electrical equipment of the EDG system shall have immunity against radiated and conducted interferences. In addition the equipment shall have sufficiently low EMC emissions. Normally compliance against typical industrial norms for given EM environments is considered adequate. Special attention in the NPP environment can be paid to so called high-power electromagnetic pulses (HEMP), which are man-made. [12, 84]

7.6.2 Design service life

The design service life of the EDG indicates that time period between when the EDG is installed for the real NPP service for the first time and the time when the EDG has reached its limits of operating hours or/and operational cycles. Basically, the design service life of the EDG is aligned with the NPP operating service life. Depending on the customer’s requirements and the manufacturer’s technical specifications, the design service life is always determined and agreed project specifically. Typically the design service life span for the EDGs is between 40 – 60 years. For example, according to IEEE 387 standard, the design service life of the EDG is defined as follows (values include margins): [28]

- Operational cycles: as a minimum 4000 starts over a period of 40 years (average 100 starts per year);
- Operating hours: as a minimum 6000 hours over a period of 40 years (average 150 operating hours per year).

In the case, when the EDG design service lifetime is about to be reached, normal procedure is that it’s allowed that the EDG lifetime can be extended (refurbishment project). The necessity of the extension shall be evaluated based on assessments of technical conditions of the EDG unit and its equipment. Also the assessment of the remaining service life shall be evaluated and analyzed thoroughly. Such factors, which may remarkably degrade the lifetime of the EDG are for example periodically occurring severe operating conditions (ambient conditions), aging phenomena of certain important safety-related components and their materials (e.g. insulation materials, bearings) and possible severe failures or malfunctions of the EDG components (e.g. generator short-circuits). [28, 71]

7.6.3 Reliability aspects

The reliability of the EDGs can be one of the main factors contributing the risk of core damage due to SBO event occurring in the NPP, as stated in NRC RG 1.9. In addition, according to NRC RG 1.155, the reliability of the EDGs should be used as one of the factors in determining duration of time for the NPP that it should be able to cope or survive from the SBO. For example, if all other factors (such as redundancy of the EDGs, LOOP frequency and probable duration of time needed to restore off-site power back to the NPP) remain constant, a greater reliability of the EDGs will result in a lower probability of the SBO events occurring. [64, 85]

It is important that required reliability of the EDGs has been achieved before placing them into real nuclear service (i.e. by means of design, analysis, qualification methods, testing etc.), and the operational reliability during service is maintained at high level (i.e. by means of periodical testing, condition monitoring, maintenance, root cause analysis of all failures related to EDGs etc.) over the service life time. NRC RG 1.9 includes recommendation that this could be achieved by initiating a reliability program designed specifically to monitor, improve and maintain the operational reliability of the EDGs. Based on NRC RG 1.155, the minimum reliability of the EDGs should be targeted at 0.95 (95 %) or 0.975 (97,5 %) per demand depending on the NPP characteristics and the NPP operating licensee objectives. [64, 85]

Start and load-run reliability

NSAC 108 (The Reliability of Emergency Diesel Generators at U.S. Nuclear Power Plants) reliability study proposes the general criteria for classifying EDG starts and load-runs as success and failures. Based on NSAC 108, the reliability of the EDG is considered to have two elements, which are start reliability and load-run reliability. NSAC 108 also determines that the EDG operation consists of two phases; the start phase and the load-run phase. The start phase ends when the EDG begins a countable load-run or is shut down. The products of start reliability and load-reliability produce the EDG reliability as follows: [86]

$$\text{Start reliability} = \frac{\text{Number of successful starts}}{\text{Total number of valid demands to start}} \tag{1}$$

$$\text{Load-run reliability} = \frac{\text{Number of successful load-runs}}{\text{Total number of valid demands to load}} \tag{2}$$

$$\text{EDG reliability} = (\text{start reliability}) \times (\text{load-run reliability}) \tag{3}$$

Consistent with NSAC 108 expressions, definitions of start and load-run demands and failures as well as for exception cases can also be found from NRC RG 1.9, which are summarized in Appendix B. [64]

Databases and reliability studies

There are different international and national databases that keep record of NPP events/incidents. These databases also include essential statistical history data of EDG operating experience with the NPPs. Such databases are for example the IRSN (Institut de Radioprotection et de Sûreté Nucléaire) SAPIDE, the GRS (Gesellschaft für Anlagen und Reaktorsicherheit mbH) VERA, the U.S. NRC Licensee Event Reports (LERs) and the IAEA International Reporting System (IRS). The recorded data from these sources can been utilized for example to produce EDG reliability studies so that all factors that may have contribution to the EDG related failures can be revealed and analyzed thoroughly. To get deeper knowledge of the EDG reliability and related failures (e.g. failure modes, common cause failures (CCFs), failure distribution between EDG auxiliary systems and components etc.) the following studies are recommended: NSAC 108 (1986) [86], NUREG/CR-5500 (1999) [87], NUREG/CR-6819 (2003) [88] and EU Clearinghouse Topical Study of EDG Operating Experience (2013) [89]. [86; 87; 88; 89]

8 DISCUSSION AND CONCLUSIONS

8.1 Overview

The main goal of this master's thesis was to examine the major performance requirements and related characteristics of the nuclear EDG system that works as an on-site emergency power safety system for the NPP. By doing so, this thesis aimed to improve the understanding of the importance, role and functional side of the EDG system operating as a safety system of the NPP; regulatory framework and relevant standards; specific requirements and features; qualification aspects; and other EDG related topics in general.

The overarching research question that guided this work was: ***What are the most important performance requirements specific to the nuclear EDG system?*** This chapter responds to this question by providing a summary, main findings and conclusions in the light of the research objectives presented in Chapter 1.

8.2 Role and importance

This study confirms that the EDG system plays an important role in ensuring the NPP safety. The EDG system represents highly critical safety equipment for the NPP when it needs to survive from possible occurring emergency events. Based on the Fukushima NPP accident, the contribution of the availability and reliability of the EDGs to the NPP's capability to cope with different emergency events (e.g. LOOP, SBO) is considered undeniable.

To briefly summarize the purpose of the EDG system, it is particularly designed for staying in stand-by mode long periods of time, starting-up imminently in response to start-up signal, and supplying emergency power to the NPP. On emergency demand, the EDG produces alternative current (AC) electricity to the NPP's safety auxiliaries (engineered safety features, ESF) in case the NPP experiences for example a loss-of-offsite power (LOOP) event. In turn, the NPP's safety auxiliaries are designed to maintain the reactor in safe state during emergency event and bring the NPP into safe shutdown condition. Especially in the case of an extended LOOP event, it is important that the EDG can feed emergency power as long as necessary (e.g. for a duration of several days) so that regular off-site power supply is restored. The NPP's emergency load types that the EDG is feeding consist of, for example, cooling and circulation pumps of the reactor, control power batteries, fire detection systems and other safety related power loads.

In order to ensure that the EDG system can perform its intended purpose (necessary safety functions) reliably and independently without interruptions on emergency demand, it is essential that the nuclear safety design principles (redundancy, separation, diversification, simplicity, fail safe, independency) are applied to the EDG system's design from the beginning of the EDG project initiation. However, it should be noted that while the design principles of the nuclear industry are mandatory to comply with, and if all these principles are followed in designing nuclear applications such as the EDG system without any deviation arrangements, it is highly likely that the application will become complex rather than simple. The more complex system, the higher chance for uncertainty factors to weaken the overall reliability. Compliance of the nuclear safety criteria throughout all stages of the design of nuclear applications contributes to this complexity.

8.3 Regulatory framework and standards

As to the regulatory framework, the nuclear application manufacturer/supplier (e.g. Wärtsilä) needs to comply with the regulations that originate from various sources: national government (where the NPP is located and business is done), international and national level authorities (IAEA, regulatory body e.g. STUK in Finland), a customer (NPP owner, licensee holder) and a manufacturer itself. Especially IAEA and the national level authority (regulatory body) play important roles in the regulatory framework. IAEA states that the national regulatory body (e.g. STUK) should have a reactive approach, which makes it easier for the nuclear application manufacturer to optimize the design of the equipment. For example, this is the case in Finland, but it should be demonstrated that designed alternative solutions fulfill the requirements defined by STUK.

Regulatory frameworks of the United States and Germany were also looked briefly into in this study. The U.S. regulatory framework can be seen performance based, i.e. focusing on continual improvement. Regulations and guidelines set the targets, but these provide also opportunity to decide manners for achieving the goals. On the contrary, the German regulatory framework is compliance based, wherein regulations and laws set the goals, but also define the means quite accurately to achieve them. Finnish regulatory framework has features from both U.S. and German frameworks.

Corresponding broadness of the regulatory framework and regulation sources, there is also a wide range of international and national standardization (nuclear specific and industrial standards, codes, norms and guidelines) applicable to the EDG system. The nuclear specific standards are developed specifically to provide the principal criteria of design, qualification, performance, and testing requirements for the EDG system's equipment. For example, YVL-Guides developed by STUK are not legally binding, but they are intended to provide guidance and recommendations for the manufacturers and operators of nuclear applications.

This study introduced and utilized information especially from two technical standards, which both determine nuclear specific requirements for the EDG system; KTA 3702 (Germany) and IEEE 387 (U.S.). If these standards are compared, the scope in IEEE 387 regarding the EDG equipment is wider than in KTA 3702. KTA 3702 is very detailed, but its benefit is that it includes requirements and definitions for example for the mechanical auxiliary systems whereas IEEE 387 refers to other applicable standards and may be rather vague in some extent. On the other hand, IEEE 387 seems to give more freedom to the manufacturer to decide best practices in design and qualification for achieving required level of performance and safety for the EDG system's equipment. This comparison of KTA 3702 and IEEE 387 standards directly reflects the differences between the U.S. and German regulatory frameworks as discussed above.

As the regulatory frameworks differ depending on countries' nuclear policies and regulations and applicable standardization will be revised and updated continually, the nuclear application manufacturer needs to stay up-to-date and recognize this changing environment in order to do business successfully. In addition, it is especially important that the manufacturer understands, communicates and clarifies the regulatory requirements and possible changes regarding standardization to the sub-contractors and other actors in the EDG manufacturing and equipment supply chain, and also monitors that the requirements are complied. For example, this helps to avoid possible misunderstandings and enables supplying components with better quality. Of course this arrangement demands active training, but the manufacturer should have the possibility to better monitor the sub-contractors' quality management procedure to ensure that its own quality chain retains its competitiveness and that it can be improved in the future.

When viewing the diverse nuclear regulation environment in the global scale, there may be a need to develop the standardization to be more coherent. It seems that there is also a need to clarify and unify the structures of the national level regulatory frameworks with each other as this could facilitate better designing and manufacturing of more reliable equipment through more understandable regulations and standards. Currently, it appears to be challenging to find the essential information from different standards as the technology in question encompasses almost the whole scale of engineering know-how.

The outlook for the future is that the EDG systems need to be continuously developed due to tightening safety regulations internationally aiming to improve the overall safety of the NPPs. Often the result is increased number of installed EDGs in the NPP. From the manufacturer's point of view, this will most likely provide new business opportunities when the markets will be broader. Also the manufacturer should be able to manage the content of both KTA 3702 and IEEE 387 standards to secure wide market base.

8.4 Required performance and impacting factors

The EDG system was comprehensively examined in this study based on Wärtsilä's solutions. From this thorough review, it is determined that the whole EDG system can be considered one single entirety consisting of multiple connected mechanical and electrical components as well as supporting auxiliary systems. These all have to operate seamlessly together for a common purpose so that the EDG system has the capability to perform as required. The main functions of each component of the EDG set (engine, generator and common base frame) and connected sub-systems (auxiliary systems, E&A-system and I&C-system) correspond to those required functions presented in applicable technical standards (KTA 3702, IEEE 387) and guides (NRC RG 1.9).

The most important performance requirements of the EDG system can be highlighted by examining these criteria from the perspectives of the EDG system's intended purpose and necessary safety functions when selected for the real nuclear service as an on-site emergency power supply in the NPP. On the basis of this study, the required performance capabilities of the EDG system (considered as a single unit) are summarized as follows:

During emergency operation – capability to:

- Perform necessary safety functions (safety missions) under predefined conditions in the event of emergency: start-up, accept load and maintain load;
- Start-up as soon as possible in response to emergency demand such in the case of LOOP and as the NPP design requires (typical required start-up time frame is 10 – 15 seconds from receiving start signal including safety margin);
- Start-up even without no cooling available momentarily (cooling needs to be restored in acceptable time frame);
- Accept load within acceptable time frame after start-up when frequency and voltage limits are within acceptable limits (readiness for load acceptance);
- Accelerate heavy motor loads (block of loads of the NPP's safety auxiliaries, engineered safety features, ESF) in rapid succession (sequence) according to the NPP's load profile;
- Take large load steps according to the NPP's load profile (single load step of at least 50 % of the EDG's design load);
- Recover in acceptable time frame from loading transients within loading sequences (dynamic tolerances of speed, frequency and voltage);
- Maintain load within acceptable frequency and voltage limits at the design load (static tolerances at the continuous load rating);

- Operate at the over-load (short-time load) power (up to 110 % of the design load) if necessary for a specified duration of time;
- Supply emergency power to the NPP's safety auxiliaries as long as necessary until regular power supply connection with the off-site grid is restored (i.e. for a duration of several days in case of an extended LOOP event);
- Shutdown (stop operating) securely and immediately only by means of predefined safety principles (2-out-of-3 protection logic) to prevent breakdown (if experiencing the engine overspeed, high HT-water temperature, low lubricating oil pressure, generator overcurrent or generator differential current).

Under testing conditions at different loads – capability to:

- Start-up, accept load, accelerate load and maintain load under testing conditions according to the testing programs;
- Operate at the design load (continuous load rating including safety margin) under testing conditions;
- Operate at the over-load (short-time load) power (up to 110 % of the design load) under testing conditions for a specified duration of time;
- Operate at the light-load (short-time load) and no-load (idling) under testing conditions for a specified duration of time as required by the equipment specification (typically according to the manufacturer's recommendations).

Other capabilities:

- Withstand long periods of time in the stand-by mode waiting for instant start-up command and maintain availability for emergency or testing operation (with necessary facilitation systems running for fast start-up, i.e. pre-heating and pre-lubricating);
- Monitor, indicate condition, and protect the EDG system's equipment during any operation mode;
- Operate at any load without any excessive vibration (vibration isolation during start-up, loading and damping against seismic forces);
- Operate under the most unfavorable ambient conditions (withstand abnormal conditions, extreme weather and natural phenomena, external hazards, electrical disturbances and other interferences);
- Operate and be functional during and after any design basis event (DBE) (i.e. during and after the earthquake);
- Operate at any operation mode as reliably as required (achieving demanded start-up and load-run reliability according to the minimum target reliability level, i.e. 95 % per demand);
- Operate independently without any external source of electricity (island operation) and causing no interference to other safety systems in the NPP.

There are also a number of impacting factors that may degrade or disturb the EDG system's performance and reliability during its operation in the nuclear service. In worst case, influence of these factors (individual or combined effect) may possibly lead to a severe failure of a safety related component or system, which may eventually cause unavailability situation of the EDG system. This in turn means that it will not be capable of performing its necessary safety functions as required when the actual emergency demand occurs. Based on this thesis work, the following impacting factors are identified:

- Operating related factors: fast starts, heavy/rapid loading, volatile loading sequences, long durations of time in stand-by mode, vibrations during operation etc.;
- Environmental conditions related factors: varying abnormal conditions, extreme weather, external hazards, electrical disturbances, etc.;
- Aging related factors: component and materials aging phenomena;
- Operating media related factors: operating media characteristics (fuel oil, lubricating oil, cooling water), long term storage, compatibility with materials, etc.;
- Design, qualification and maintenance related factors: design and maintenance flaws, human made errors, insufficient sizing of components, wrong material selection, etc.

8.5 Qualification

As to the qualification, it plays an essential role in ensuring that the EDG system achieves an appropriate level of quality and demanded capability for the actual nuclear service with the NPP. The main purpose of the qualification is to demonstrate and verify that the design, performance, reliability and other characteristics will be obtained before the EDG system is installed for the service. The complete qualification process includes a number of methods that consist of various analyses, calculations, tests and simulations. After successfully conducted qualification, the EDG system achieves qualified design service lifetime, which is typically 40 – 60 years.

This study introduced and described the main qualification procedures that typically are carried out by the EDG manufacturer: the safety grading, technical performance qualification, and environmental qualification. The safety grading is typically the first step of the qualification process, and it enables classification and categorization of the EDG system's equipment (individual components and sub-systems) into different safety classes based on their safety related significance and functions. Both domains of the EDG system, electrical and mechanical, can be subjected to functional and structural categories by means of the safety grading. As a result of the safety grading, certain EDG components and sub-systems are classified as either safety-related (SR) or non-safety related (NSR) categories, and this knowledge supports the complete execution of the EDG project.

The technical performance qualification consists of analysis and testing parts. Both of them aim to demonstrate that the EDG system as a single unit has the capability to perform its intended functions, and that all components and sub-systems meet their associated technical performance requirements defined in applicable standards and project specific technical specifications. The analysis is normally done inside the design process of the EDG system, but it is often also combined with the testing to provide more accurate and reliable results. The performance testing examined in this study consists of three main programs based on IEEE 387 standard: the factory production/acceptance testing (FAT), type testing and site testing. FAT and type testing are normally conducted at the manufacturer's or assembler's testing facility, and site testing followed by these is performed at the NPP site location. Each of these testing programs include a number of sub-tests, which put the EDG through several rigorous and challenging tests that demonstrate the EDG's performance (i.e. starting and loading capabilities) in different operating conditions.

The environmental qualification consists of aging and seismic qualification procedures based on IEEE 344 and IEEE 323 standards. Typically, all SR electrical equipment (Class 1E) of the EDG system is subjected to the aging qualification so that possible aging related stressors and mechanisms can be identified, which may degrade the performance of the EDG system and related equipment over time. The aim of this is to demonstrate that the SR electrical equipment can perform its intended safety related functions before, during, and after applicable DBE, and without experiencing any failures. The seismic qualification proves that the EDG equipment has the capability to perform associated safety functions during and after earthquake. The seismic qualification is typically required for all SR components of the EDG system, and recommended methods includes analysis, testing, combination of analysis and testing, and use of operating experience data. The safety grading provides an important baseline for supporting the aging and seismic qualification procedures.

8.6 Future research

Worldwide, new nuclear power plants will be designed and constructed in the future according to tightening nuclear safety regulations. This clearly suggests that the nuclear safety applications (such as the EDG system) need to be developed to the same extent to fulfill these stricter requirements. For example, it would be interesting to investigate what benefits can be reached or what the possible disadvantages for the EDG's performance are if using the digital control system instead of the analogue type, which is currently the traditional solution mainly due to its simplicity and reliability. Another valid topic for further research could be to examine what kind of limitations the use of low emission fuel oil blends (e.g. biofuel) and the diesel engine gaseous emission controlling pose to the EDG's performance in the nuclear service.

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APPENDICES

APPENDIX A: SUMMARY OF EDG TESTING PROGRAMS – IEEE 387 FACTORY PRODUCTION/ACCEPTANCE TESTING (FAT)

Factory production/acceptance testing (FAT) program (acc. IEEE 387)	
Sub-test	**Definitions and requirements**
Engine tests	• Each engine shall be tested such that a generator or a water brake dynamometer is utilized to provide accurate means to control power absorption. • The following tests shall be carried out for the engine: a) Break-in test: Each manufacturer shall develop their own break-in schedule to best suit the engine. b) Performance test: 1) Test runs: After the engine has satisfactorily completed the break-in test, the following minimum tests shall be performed to establish the operating characteristics. These tests may be executed in any order desired. • 1 hour at 50 % of continuous load rating (low-load) • 1 hour at 75 % of continuous load rating • 2 hours at 100 % of continuous load rating (rated load) • 2 hours at 110 of continuous load rating (overload) 2) Data logging: Test logs of all of the above tests shall become a part of the records for a particular engine. The test logs shall include at least the data specified in IEEE 387 standard. 3) Controls-alarm and shutdown: All engine-mounted alarms and shutdowns, where applicable, shall be set and checked. The points of actication shall be on the test logs. 4) Inspection: At any point after break-in test or upon completion of the above test, a post-trial inspection shall be conducted. The standard procedure of the manufacturer shall be used. The inspection results shall be documented in the test report.
Generator tests	• The generator testing shall be done in accordance with NEMA MG 1-1993.
Tests of excitation, control, and other accessories/auxiliaries	• All such devices and assemblies shall be tested in accordance with the standard practices of the manufacturer.

APPENDIX A: SUMMARY OF EDG TESTING PROGRAMS – IEEE 387 TYPE TESTING

Type testing program (acc. IEEE 387)	
Sub-test	**Definitions and requirements**
Load capability tests	• Demonstrate the capability of the EDG unit to carry the following rated loads at rated power factor for the period of time indicated, and to successfully reject load. a) Load equal to the continuos rating shall be applied for the time required to achieve temperature equilibrium of the engine. b) Immediately following step a), the short-time rated load shall be applied for a period of 2 hours and the continuous rated load shall be applied for a period of 22 hours. c) The short-time rating load reject test shall be conducted. This test will acceptable if speed increase of the engine does not exceed 75 % of the difference between nominal speed and the overspeed trip set point, or 15 % above nominal, whichever is lower. d) Light-load or no-load capability shall be demonstrated by test. In this test light-load or no-load operation shall be followed by a load application ≥ 50 % of the continuous kilowatt (kW) rating for a minimum of 0.5 hour.
Start and load acceptance tests	• A total of 100 valid start and load tests with no failures shall be performed. • In case failure of the EDG unit to successfully complete this series of tests occurs, this will require a review of the system design adequacy, the cause of the failures to be corrected, and the tests continued untila 100 valid tests are accomplished without any failure. • The start and load tests shall be performed as follows: a) Cranking of the engine shall begin upon receive of the start-diesel signal, and the EDG unit shall accelerate to specified frequency and voltage within the required time frame. b) Immediately after step a), the EDG unit shall accept a single-step load ≥ 50 % of the continuous kilowatt (kW) rating. The load may be totally resistive or a combination of resistive and inductive loads. c) At least 90 of these tests shall be executed with EDG unit initially at warm stand-by condition, based on jacket water and lubricating oil temperatures at or below values recommended by the engine manufacturer. After load is applied, the EDG unit shall continue to operate until jacket water and lubricating oil temperatures are within ± 5.5 °C (± 10 °F) of the normal engine operating temperatures for the corresponding load. d) At least 10 tests shall be performed with the engine initially at normal operating temperature equilibrium defined as jacket water and lubricating oil temperatures within ± 5.5 °C (± 10 °F) of normal operating temperatures, as established by the engine manufacturer for the corresponding load. e) If the cause for failure to start or accept load in accordance with the preceding sequence falls under any of the categories listed below, that particular test shall be disregarded, and the test sequence shall be resumed without penalty following identification and correction of the failure cause for the unsuccessful attempt. 1) Unsuccessful start attemps that can definitely attributed to operator error, including setting of alignment control switches, rheostats, or potentiometers, or other adjustments that may have been changed inadvertently prior to that particular start test. 2) Tests conducted for verification of a scheduled maintenance procedure required during this series of tests. This maintenance procedure shall be defined prior to conducting the start and load acceptance tests and will then become a part of the normal maintenance schedule after 3) Tests performed in the process of troubleshooting. Each start attempt performed in the troubleshooting process shall be defined as such before a start attempt is made. 4) Successful start attempts that were terminated intentionally without loading. 5) Failure of any of the temporary service systems such as DC power source, output circuit breaker, load, interconnecting piping and wiring, and any other temporary setup that will not be a part of the permanent installation.
Margin tests	• The criteria for margin tests are as follows: a) Demonstrate the ability of the generator and excitation system to accept the margin test load (usually the low power factor (PF), high inrush, and high starting current of a pump motor) without experiencing instability resulting in generator voltage collapse, or significant evidence of the inability of the voltage to recover. b) Demonstrate that there is sufficient engine torque available to prevent engine stall, and to permit the engine speed to recover, when experiencing the margin test load.

APPENDIX A: SUMMARY OF EDG TESTING PROGRAMS – IEEE 387 SITE ACCEPTANCE TESTING (SAT)

Site acceptance testing (SAT) program (acc. IEEE 387)	
Sub-test	**Definitions and requirements**
Starting test	• Demonstrate the capability to attain and stabilize frequency and voltage within the limits and time determined in the equipment specification
Load acceptance test	• Demonstrate the capability to accept the individual loads that make up the design load in the desired sequence and time duration and to maintain the voltage and frequency within acceptable limits • In case the EDG has a light-load or no-load (idling) operation capability, this test sequence shall include consideration of potential effects on load acceptance following such operation.
Rated load test	• Demonstrate the capability of carrying the following loads for the indicated times without exceeding the manufacturer's design limits: a) A load equal to the continuous rating for the time required to reach engine temperature equilibrium plus (+) 1 hour b) Immediately following the load in item a), the rated short-time load shall be applied for a period of 2 hours
Load rejection test	• Demonstrate the capability of rejecting short-time rated load without exceeding speeds or voltages that will cause tripping or component damage.
Electrical test	• Demonstrate that the electrical properties of the generator, excitation system, voltage regulation system, engine governor system, and the control and surveillance systems are acceptable for the intended application.
Subsystem test	• Demonstrate the capability of the control, protection, and surveillance systems to function in accordance with the requirements of the intended application.
Test loads	
Test loads that will be applied, carried, and rejected during the site testing shall be design load auxiliaries located at the station (NPP). Equivalent loads may be used if these auxiliaries cannot be operated for testing.	

APPENDIX A: SUMMARY OF EDG TESTING PROGRAMS – IEEE 387 PRE-OPERATIONAL TESTING

Pre-operational testing program (acc. IEEE 387)	
Sub-test	**Definitions and requirements**
Reliability test	• Demonstrate that an acceptable level of reliability has been achieved to place the new EDGs into operation. • This shall be achieved at least by 25 valid start and load tests without failure on each installed EDG.
Loss-of-offsite power (LOOP) test	• Demonstrate by simulating LOOP that a) The emergency buses are de-energized and the loads are shed from the emergency buses. b) The EDG unit starts on the auto-start signal from its stand-by conditions, attains the required voltage and frequency within acceptable limits and time, energizes the auto-connected shut-down loads through the load sequencer, and operates for a minimum of 5 minutes.
Safety injection actuation signal (SIAS) test	• Demonstrate that on a SIAS, the EDG unit starts on the auto-start signal from its stand-by conditions, attains the required voltage and frequency within acceptable limits and time, and operates on stand-by for a minimum of 5 minutes.
Combined SIAS and LOOP test	• Demonstrate by simulating LOOP in conjuction with SIAS that a) The emergency buses are de-energized and the loads are shed from the emergency buses. b) The EDG unit starts on the auto-start signal from its stand-by conditions, attains the required voltage and frequency within acceptable limits and time, energizes the auto-connected shutdown loads through the load sequencer, and operates for a minimun of 5 minutes.
Largest-load rejection test	• Demonstrate the capability of the EDG unit to reject a loss of the largest single load, and verify that the voltage and frequency requirements are met and that the EDG unit will not trip on overspeed.
Design-load rejection test	• Demonstrate the capability of the EDG unit to reject a load equal to 90 – 100 % of the design loads, and verify that the EDG unit will not trip on overspeed.
Endurance and load test	• Demonstrate load-carrying capability for an interval of not less than 8 hours, of which 2 hours should be at a load equivalent to the short-time rating of the EDG unit and 6 hours at a load equivalent to 90 – 100 % of the continuous rating. • For the pre-operational test, durations are 2 hours at short-time rating and 22 hours at 90 – 100 % of the continuos rating • Verification that voltage and frequency requirements are maintained.
Hot restart test	• Demonstrate hot restart functional capability at full-load temperature conditions by verifying that the EDG unit starts on a manual or auto-start signal, attains the required voltage and frequency within acceptable limits and time, and operates for a minimum of 5 minutes.
Synchronizing test	• Demonstrate the ability to a) Synchronize the EDG unit with offsite power while the unit is connected to the emergency load. b) Transfer this load to the offsite power. c) Isolate the EDG unit. d) Restore the EDG unit to stand-by status.
Protective-trip bypass test	• Demonstrate that specified automatic EDG unit trips are automatically bypassed as designed. • Typically, the engine overspeed and generator differential current trip are not bypassed.
Test mode override test	• Demonstrate that with the EDG unit operating in the automatic test mode while connected to its bus, a simulated safety injection signal (SIAS) overrides the test mode by a) Returning the EDG unit to stand-by operations. b) Automatically energizing the emergency loads from offsite power.
Independence test	• Demonstrate that, by starting and running (unloaded) redundant EDG units simultaneously, potential common failure modes that may be undetected in single EDG unit tests do not occur.

APPENDIX A: SUMMARY OF EDG TESTING PROGRAMS – IEEE 387 AVAILABILITY TESTING

Periodic testing program – Availability tests (acc. IEEE 387)	
Sub-test	**Definitions and requirements**
Slow-start test	• Demonstrate proper start-up from stand-by conditions and verify that the required design voltage and frequency are attained. • The EDG unit should achieve rated speed on a prescribed schedule selected for minimizing stress and wear on the EDG unit.
Load-run test	• Demonstrate load-carrying capability, with load equivalent to 90 – 100 % of the continuous rating of the EDG unit, for an interval not less than 1 hour and until temperature equilibrium has been attained. • This test may be accomplished by synchronizing the EDG generator with off-site power. • Testing may be performed at unity power factor or at a lagging power factor within the EDG unit capability. • The loading and unloading of the EDG unit during this test should be gradual and based on a prescribed schedule selected for minimizing stress and wear on the EDG unit.
Fast-start test	• Demonstrate that each EDG unit starts from stand-by conditions (if a plant has normally operating pre-warm systems, this would constitute its stand-by conditions) and verify that the EDG unit reaches required voltage and frequency within acceptable limits and time, as defined in the plant technical specifications.

APPENDIX B: SUMMARY OF EDG START AND LOAD-RUN DEMANDS AND FAILURES – NRC RG 1.9

Definitions of start demands and failures (acc. NRC 1.9)
Start demands
• All valid and inadvertent start demands, including all start-only demands and all start demands that are followed by load run demands, whether by automatic or manual initiation, are start demands. • In a start-only demand, the EDG is started, but no attempt is made to load the EDG unit.
Start failures
• Any failure within the EDG system that prevents the generator from achieving a specified frequency (or speed) and voltage within specified time allowance is classified a valid start failure. • For monthly surveillance tests, the EDG can be brought to rated speed and voltage in the time recommended by the manufacturer to minimize stress and wear. • Any condition identified during maintenance inspections (with the EDG in the stand-by mode) that would be definitely have resulted in a start failure if a demand had occurred should count as a valid start demand and failure.
Definitions of load-run demands and failures (acc. NRC 1.9)
Load-run demands
• To be valid, the load-run attempt should follow a successful start and meet one of the following criteria (see exceptions): • A load-run of any duration that results from a real (i.e., not a test) automatic or manual signal. • A load-run test to satisfy the plant’s load and duration test specifications. • Other operations (e.g. special tests) in which the EDG is planned to run for at least 1 hour with at least 50 % of the design load.
Load-run failures
• A load-run failure should be counted when the EDG starts but does not pick-up the load and run successfully. • Any failure during a valid load-run demand should count (see exceptions). • For monthly surveillance tests, the EDG can be brought to rated speed and voltage in the time recommended by the manufacturer to minimize stress and wear. • Any condition identified during maintenance inspections (with the EDG in the stand-by mode) that definitely would have resulted in a load-run failure if a demand had occurred should count as a valid load-run demand and failure.
Exception cases of start and load-run demands or failures (acc. NRC RG 1.9)
• Unsuccessful attempts to start and load-run should not count as valid demands or failures when they can definitely be attributed to any of the following cases: • Any operation of a trip that would be bypassed in the emergency operation mode (e.g., high cooling water temperature trip). • Malfunction of equipment that is not required to operate during the emergency operation mode (e.g., synchronizing circuitry). • Intentional termination of the test because of alarmed or observed abnormal conditions (e.g., small water or oil leaks) that would not have ultimately resulted in significant damage or failure of the EDG. • Component malfunctions or operating errors that did not prevent the EDG from being restarted and brought to load within 5 minutes (i.e., without corrective maintenance or significant problem diagnosis). • A failure to start because of a portion of the starting system was disabled for test purposes, if followed by a successful start with the starting system in its normal alignment.